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Trophic Classification of Selected Colorado Lakes

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SUBJECT: Errata

Please note the following corrections to JPL Publication 78-100, Trophic Classification of Selected Colorado Lakes, by Richard J. Blackwell and Dale H. P. Boland, dated January 1979:

Page 5-1, paragraph (2):
Line 1, change "MSS and MSS" to "MMS and MSS"
Line 5, change "MSS-related" to "MMS-related"

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TROPHIC CLASSIFICATION OF SELECTED COLORADO LAKES

Lake Classification Through the Amalgamation of Contact-Sensed Data and Digitally Processed Multispectral Scanner Data Acquired by Satellite and Aircraft

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ABSTRACT

Multispectral scanner data, acquired over several Colorado lakes using Landsat-1 and aircraft, were used in conjunction with contact-sensed water quality data to determine the feasibility of assessing lacustrine trophic levels. A trophic state index was developed using contact-sensed data for several trophic indicators (chlorophyll a, inverse of Secchi disc transparency, conductivity, total phosphorous, total organic nitrogen, algal assay yield). Relationships between the digitally processed multispectral scanner data, several trophic indicators, and the trophic index were examined using a supervised multispectral classification technique and regression techniques. Statistically significant correlations exist between spectral bands, several of the trophic indicators (chlorophyll a, Secchi disc transparency, total organic nitrogen), and the trophic state index. Color-coded photomaps were generated which depict the spectral aspects of trophic state. Multispectral scanner data acquired from satellite and aircraft platforms can be used to advantage in lake monitoring and survey programs when amalgamated with contact-sensed data.

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SECTION I

INTRODUCTION

Limnologists and other scientists concerned with eutrophication have frequently become entangled in the semantics associated with the word "eutrophication." Originally the term was limited to the concept of changes in the nutrient levels in lakes, but has now broadened in meaning to include the consequences of nutrient enrichment.

Eutrophication of surface waters is a major contemporary water quality management problem. Many of man's activities accelerate naturally occurring eutrophication. Municipal sewage and industrial waste disposal activities as well as land use practices often impose relatively large nutrient loadings on lakes and rivers. In some cases, this enrichment results in algae blooms and other symptoms of eutrophication. The consequences of man-induced eutrophication often make the water body less attractive to potential users, or completely unusable. More importantly, at least when a long-range viewpoint is adopted, eutrophication shortens the time period of natural lake succession.

A. THE NATIONAL EUTROPHICATION SURVEY

In December 1971 the U. S. Environmental Protection Agency (EPA) announced initiation of the National Eutrophication Survey (NES), an intensive survey to identify water bodies in the United States which have potential or actual eutrophication problems due to phosphorus from municipal sources and assess the degree of this problem. Establishment of the survey project was announced jointly by the Surgeon General of the United States, the Administrator of EPA, the Commissioner of the Food and Drug Administration, and the Chairman of the Council on Environmental Quality. They further announced that nitrilotriacetic acid should not be used as a phosphate substitute because of unresolved questions concerning long-term effects on human health and the environment.

The results of the Eutrophication Survey have been integrated into an EPA control program. Through construction grants to state and local governments, this program will seek to improve municipal waste treatment facilities so as to reduce phosphate levels to the extent necessary to protect water quality.

It should be noted that the survey centered upon phosphorus and nitrogen, the nutrients most often implicated as a cause of eutrophication in freshwater and, occasionally, in salt or brackish water. While the process and rate of eutrophication within any particular water body can also be related to other substances including elements such as iron, manganese, and molybdenum, nitrogen and phosphorus, in particular, play key roles.

For each lake considered, the work of the Eutrophication Survey consisted of three actions, undertaken in response to three fundamental questions:

	Question	Action
(1)	What is the water body's trophic condition and what are the nutrient levels at the present time?	Assess lake's condition.
(2)	Which nutrients control the growth of aquatic plant life and can they be controlled?	Determine limiting nutrient(s).
(3)	What is the extent of nutrient loading from sources supplying the water body and, specifically, how much is from municipal sewage treatment plants?	Estimate the nutrient loading to the water body.

Responsibility for conducting the survey was assigned jointly to the EPA's Environmental Monitoring and Support Laboratory in Las Vegas, Nevada (EMSL-Las Vegas), and Corvallis Environmental Research Laboratory, Oregon (CERL)[1]. The EPA was supported by National Guard volunteers, who collected samples from tributary streams (a project sanctioned by the Department of Defense), and by local sewage treatment plant operators, who collected effluent samples.

During the first "sampling season," from March to November 1972, about 235 lakes in Minnesota, Wisconsin, Michigan, New York, and the New England states were sampled, as were some 1100 stream sites and 230 waste effluents.

In October 1972, the Congress enacted the Federal Water Pollution Control Act Amendments (PL 92-500), which assigned to the states responsibility for classifying lakes within their boundaries as to degree of eutrophication, defining the cause and nature of lake pollution, and devising procedures for eutrophication control. In response to the new Federal legislation, NES program objectives were recast to better match EPA strategies. The NES sampling program, which had previously been limited to lakes directly subject to pollution from point sources, was broadened to include lakes subject to only non-point-source pollution.

In 1973, about 250 lakes and their tributaries were sampled. These lakes are located in 17 states east of the Mississippi River and south of the states in which lakes had been sampled the previous year.

---

[1] EMSL-Las Vegas was formerly named the National Environmental Research Center-Las Vegas (NERC-Las Vegas), CERL was named the National Environmental Research Center-Corvallis (NERC-Corvallis).

About 180 lakes in the 10 Great Plains States located between the Rocky Mountains and the Mississippi River were sampled in 1974. During 1975, the last NES field year, some 155 lakes located in the remaining 11 Rocky Mountain and Far Western States were sampled. A grand total of some 820 lakes was sampled during the project (Figure 1-1).

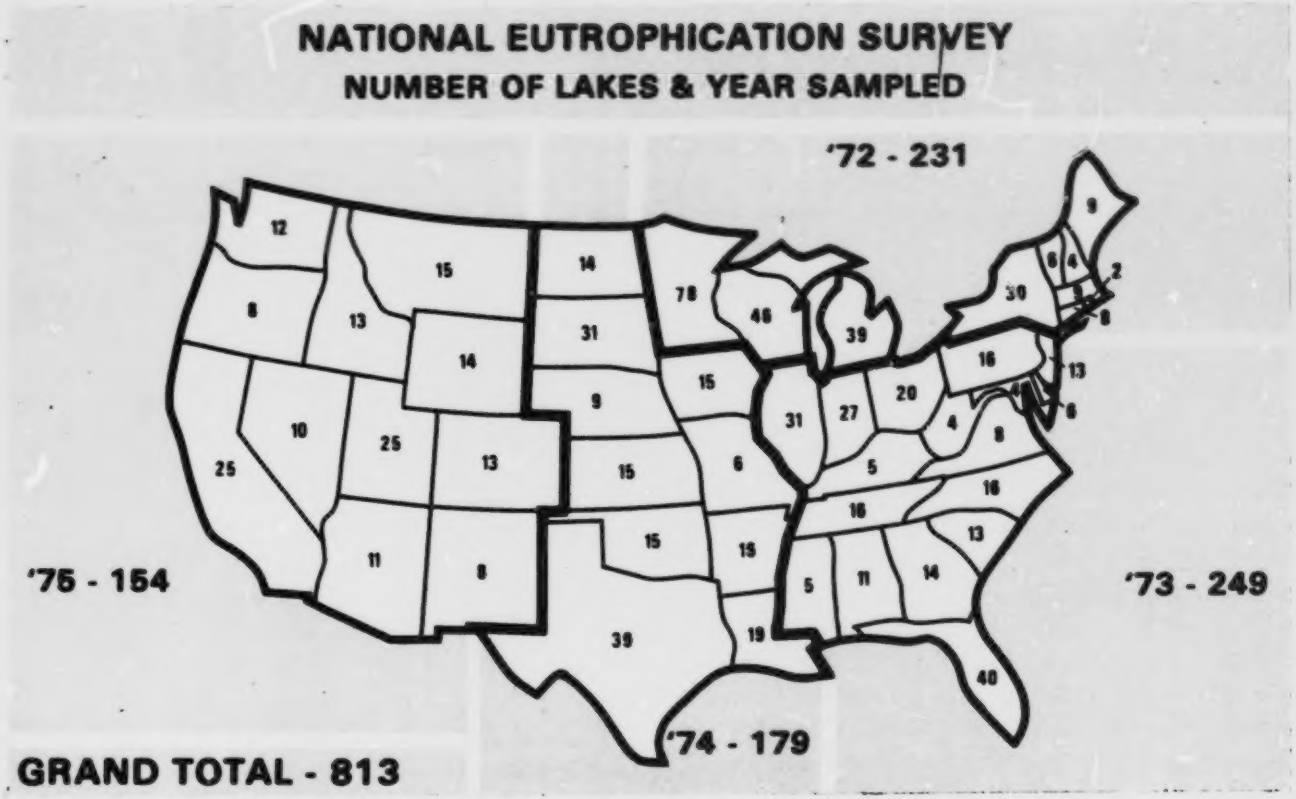
To conduct the sampling, the EPA used three Bell UH-1H "Huey" helicopters on loan from the U.S. Army. Two of the helicopters were deployed at field locations at a given time, while the third was out of service, on a rotating basis, for routine maintenance. Each of the helicopter sampling teams from EMSL-Las Vegas included a pilot, a limnologist, and a technician. The helicopter would land on a particular lake, and the crew would lower an electronic sensor package into the water to measure temperature, conductivity, turbidity, pH (whether acidic or basic), and dissolved oxygen continuously as the sensor package descended. Later, as the sensor package was raised, individual water samples were pumped from selected depths for more extensive laboratory analysis. Sightings of prominent landmarks were made for position information. When all of the measurements and samples had been gathered at a given point the sensor package was stowed back aboard the aircraft and the helicopter moved to a new site on the same, or another, lake.

At the end of the day, the helicopter returned to a temporary field base in the area, where the samples were unloaded and taken to a mobile field laboratory manned by chemists. There the samples were analyzed for chlorophyll a and dissolved oxygen, after which they were filtered and packed for shipment. Nutrient analyses and algae identifications were made at EMSL-Las Vegas; algal assays and heavy metal determinations were performed at CERL. The tributary stream samples collected by National Guardsmen and the treatment-plant-effluent samples submitted by plant operators were sent to CERL for chemical analyses. Detailed descriptions of the lake sampling procedures and the water sample analysis techniques are given in NES Working Paper Number 1 (U.S. EPA 1974) and NES Working Paper Number 175 (U.S. EPA 1975).

B. REQUIREMENTS OF THE FEDERAL WATER POLLUTION CONTROL ACT (PUBLIC LAW 92-500)

In October 1972 Congress enacted the "Federal Water Pollution Control Act Amendments." This act assigns to the states responsibility for classifying lakes within their boundaries as to degree of eutrophication or aging, defining the cause and nature of lake pollution, and devising procedures for control.

The act itself, a comprehensive document of 89 pages, outlines in great detail the goals and policies of the act. It further defines comprehensive programs for water pollution control, research, investigations, training, and the dissemination of information. Section 104-a-5 in particular directs the EPA administrator to establish, equip, and maintain a water quality surveillance system for monitoring purposes. The same citation further suggests that this water quality surveillance be


NATIONAL EUTROPHICATION SURVEY
NUMBER OF LAKES & YEAR SAMPLED
'72 - 231
'73 - 249
'74 - 179
'75 - 154
GRAND TOTAL - 813
12
15
14
78
46
39
9
6
4
2
30
8
8
13
14
31
16
13
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9
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Figure 1-1. Number of Lakes Sampled by the National Eutrophication Survey

conducted by utilizing wherever practicable the resources of NASA, NOAA, USGS, and the Coast Guard.

Several sections within the act, particularly 106 and 314, specifically require each state to identify and classify all publicly owned freshwater lakes within its boundaries. These requirements are noteworthy in that, in order for a state to gain assistance in the form of grants for pollution control programs or for lake restoration, it must conduct a classification of its lakes.

A lake classification system which utilizes a combination of remote and contact-sensed data, if developed to meet EPA standards of classification, offers a potentially cost-effective method whereby states can comply with PL 92-500 without a heavy investment at the state level to train and equip technical personnel to conduct lake classifications by water analysis.

C. PROJECT HISTORY AND BACKGROUND

When Landsat-1 (ERTS-1) was placed into orbit in July 1972, it became apparent that an opportunity existed to apply remote-sensing techniques to the problem of trophic classification of lakes. In 1974 a research proposal was accepted by NASA Office of Technology Utilization to examine the feasibility of lake classification using Landsat data in combination with contact-sensed data. A joint effort by the Image Processing Laboratory at JPL, the Corvallis Environmental Research Laboratory, Corvallis, Oregon and the Environmental Monitoring and Support Laboratory, Las Vegas, Nevada, was then undertaken to examine this potential application.

Landsat digital data in the form of computer-compatible tapes (CCT's) were obtained for lakes in New York, Wisconsin, and Minnesota. Water sample data from EPA's STORET (STOrage and RETrieval) information storage system were acquired for the lakes under consideration. The Landsat data and the STORET data were examined to obtain the best match possible in terms of water sample data and Landsat coverage data.

Two basic approaches for classification were undertaken during this period. The first was to develop a method and procedure to produce a numerical trophic index from the water quality measurements made by the EPA water sampling teams. The second approach was to relate the trophic index to the Landsat multispectral scanner (MSS) data and achieve classification and/or to use the MSS data to estimate either the numerical trophic index directly or one or more of the water quality parameters used to generate the trophic index.

The results from this joint activity, including many of the techniques and methods for data analysis, are found in Boland (1976), Boland and Blackwell (1975), Blackwell and Boland (1975), and Blackwell and Boland (1974). Boland (1976:1) drew the following conclusions:

(1) The Landsat-1 MSS is an effective tool for lake enumeration and for the estimation of lake surface area.

(2) Estimates of lake Secchi disc transparency and chlorophyll a levels having practical significance can be achieved through the incorporation of lake MSS color ratios in regression models. Each trophic indicator has a model which is unique to the specific date of Landsat-1 coverage.

(3) MSS color ratios can be used to estimate lake position on a multivariate trophic scale. However, each date of Landsat-1 coverage has its unique model. The models for different dates vary greatly in their predictive capabilities. The standard error of the models tends to decrease as the growing season progresses and the manifestations of eutrophication become more evident.

(4) While information relating to lacustrine trophic state can be extracted from Landsat-1 MSS imagery, either by visual inspection or through microdensitometry and optical density slicing, the maximum benefits in water-based studies can be derived only through the use of the digital data contained on the computer-compatible tapes in conjunction with automatic image processing techniques.

(5) Although Landsat-1 provides 18-day repetitive coverage, systematic times-series are difficult, if not impossible, to obtain because of excessive cloud cover on many dates of satellite coverage.

(6) The Landsat-1 MSS has utility as a supplemental data source in lake survey and monitoring programs. Its value is most apparent in situations involving large lakes and/or large numbers of lakes."

While the aforementioned project did enjoy some success, it is evident that several of the conclusions reflect and articulate areas of concern. Several deficiencies have been noted in the past study. These shortcomings, related more to procedural activity and project planning than to the underlying research effort, include

(1) The use of contact-sensed data acquired nonconcurrently with the MSS data. With one exception, the contact-sensed data were collected several days prior to (or after) Landsat passage.

(2) The unavailability of intermediate-level aircraft-acquired multispectral scanner data with which to determine the segments of the spectrum more suited for classification purposes.

(3) The unavailability of aerial photography for the determination of lake surface area.

(4) The use, by the regression models and classification maps, of average trophic indicator and MSS band values, computed

separately for each lake, as opposed to values determined at each sampling site in each lake.

(5) The fact that the thematic photomaps generated depicted only the spatial aspects of a trophic index developed using annual mean trophic indicator values, computed separately for each lake.

(6) The failure to generate thematic maps depicting the spatial aspects of some of the more obvious trophic indicators such as Secchi depth transparency or chlorophyll a.

The activity described in this report reflects efforts made to overcome the more obvious shortcomings of the previous study.

D. PROJECT OBJECTIVES

The general objective of this investigation is the further elucidation of the role of Landsat multispectral scanner data, when used with contact-sensed data, in lake monitoring and survey programs. Although the focus of attention is directed toward Landsat, data acquired from an aircraft-borne modular multispectral scanner (MMS) were also examined. Specific objectives include an evaluation of the scanners' capabilities to

(1) Estimate lake surface area.

(2) Estimate lacustrine trophic state.

(3) Estimate several trophic indicators including Secchi disc transparency and chlorophyll a.

(4) Aid in the development of lake thematic photomaps which depict specific lake trophic indicators and trophic state.

E. STUDY AREA AND LAKES

The selection of the study area and lakes was largely dictated by weather conditions and the sampling schedule laid out by Water and Land Quality Branch personnel at Las Vegas, Nevada. Initially, lakes in several western states (e.g., California, Utah, Nevada) were proposed as test lakes. A combination of factors, including the availability of NASA aircraft, weather, and EPA logistical and sampling constraints led to the selection of lakes in Colorado as the test lakes (Table 1-1). The lakes are described below. The surface area and water depth figures are taken from the literature and do not necessarily reflect the situation existing at the time of the Landsat flyover. Most of the "lakes" are actually artificial reservoirs which experience large fluctuations in surface area and depth during the summer.

Table 1-1. Colorado Lakes Included in the Study

Lake/Reservoir Name	STORET Number*	County	Latitude/Longitude	USGS Quadrangles
Barker R.	0801--	Boulder	39-58-00/105-28-54	Nederland 7.5' Tungsten 7.5'
Barr L.	0802--	Adams	39-57-32/104-45-17	Brighton 7.5' Mile High L. 7.5'
Blue Mesa R.	0803--	Gunnison	38-27-10/107-20-15	Little Soap Park 7.5' Sapinero 7.5' Carpenter Ridge 7.5' Big Mesa 7.5' McIntosh 7.5'
Cherry Creek R.	0804--	Arapahoe	39-39-11/104-51-20	Fitzsimons 7.5' Parker 7.5'
Cucharas R.	0805--	Huerfano	37-44-55/104-35-55	Maria Reservoir 7.5'
Dillon R.	0806--	Summit	39-37-20/106-03-58	Frisco 7.5' Dillon 7.5'
Grand L.	0807--	Grand	40-14-10/105-48-08	Grand L. 7.5'
Green Mt. R.	0808--	Summit	39-52-00/106-20-00	Mt. Powell 15.0'
Holbrook L.	0809--	Otero	38-03-37/103-36-06	Cheraw 7.5'
Meredith R.	0810--	Crowley	38-08-48/103-44-50	Sugar City 7.5'
Milton R.	0811--	Weld	40-14-20/104-38-15	Milton R. 7.5'
Shadow Mt. R.	0813--	Grand	36-40-50/107-40-22	Shadow Mt. 7.5' Grand L. 7.5'

*The STORET number is a six place alphanumeric label used to identify a water body down to the sampling site level. Using as an example the number 080101 and starting at the left end, the first two places identify the state (i.e., Colorado), the middle pair the lake (i.e., Barker Reservoir), and the right most pair the sampling site (i.e., site 01).

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1. Barker Reservoir (0801)

Barker Reservoir, located in Boulder County, is maintained by the Public Service Company of Colorado. It is situated in Sections 17 and 18, T1S, R72W, and Section 13, T1S, R73W. The lake was formed by constructing a 53-meter high concrete power dam across South Boulder Creek. It is open to public fishing, but boating is prohibited. The surface area measures 154 hectares and it has a maximum depth greater than 31 meters. The water depth is known to fluctuate greatly.

2. Barr Lake (0802)

Barr Lake is an irrigation reservoir located in Adams County approximately 24 km northeast of Denver. At its maximum extent it covers some 757 ha to a maximum depth of 12 m. The conservation pool has a mean area of 324 ha and a maximum depth of 2.4 m. The lake provides a diversity of habitats and is noted for its abundance of wildlife. The uniqueness of the lake has been recognized by the Colorado General Assembly and it has purchased, through the Colorado Division of Parks and Outdoor Recreation, a perpetual recreational easement from the irrigation company. Detailed plans have been formulated to develop the area, but at the same time to preserve the different habitats.

3. Blue Mesa Reservoir (0803)

Blue Mesa Reservoir is located in Gunnison County. It is the largest of the Curecanti National Recreation Area reservoirs located on the Gunnison River. The reservoir, first filled in October 1965, has a maximum depth of 104 m and a surface area of 3,662 ha, making it the largest reservoir in the state of Colorado.

4. Cherry Creek Reservoir (0804)

Cherry Creek Reservoir is located in Arapahoe County on the southeastern fringe of the Denver metropolitan area. It has a surface area of 356 ha and a maximum depth of 12.2 m. The lake, formed by damming Cherry Creek, is used for recreational fishing, water skiing, and pleasure boating. It is stocked with both rainbow trout and warm water species of fish.

5. Cucharas Reservoir (0805)

Cucharas Reservoir is located on the Cucharas River in Huerfano County. The water level fluctuates greatly; little water was found in the reservoir at the time of EPA sampling (August 22, 1975). The sampling crews reported it as being dry on September 7, 1975.

6. Dillon Reservoir (0806)

Dillon Reservoir is located in Summit County on the Blue River. It covers an area of 1,276 ha and has a maximum depth of 61 m. Water from this reservoir flows into Green Mountain Reservoir.

7. Grand Lake (0807)

Grand Lake is a natural lake located at the headwaters of the north fork of the Colorado River in Grand County. It is part of the Colorado-Big Thompson Project, which also includes five storage reservoirs and five regulation reservoirs. The lake has a surface area of 205 ha, a maximum depth of 81 m, and a mean depth of 41 m. It is connected to Shadow Mountain Reservoir by means of a water level channel. The two water bodies are operated as single entity. Water level fluctuations are limited to 0.3 m by law. See Shadow Mountain Reservoir (0813).

8. Green Mountain Reservoir (0808)

Green Mountain Reservoir is located on the Blue River in Summit County and is part of the Colorado-Big Thompson Project. It was formed by the construction of an earth and rock fill dam 94 m in height and 351 m in length. It has a surface area of 820 ha and a maximum depth of 76 m. The U.S. Bureau of Reclamation operates the reservoir for stabilizing purposes as well as for the generation of hydroelectric power. Its depth fluctuates as much as 27 m.

9. Holbrook Lake (0809)

Holbrook Lake is located in Otero County in southeastern Colorado. It lies about 8 km northeast of Swink in the Arkansas Valley. It has a maximum surface area of 272 ha and a maximum depth of 7 m. The surface area and depth vary greatly because the lake serves as a source of irrigation water. The conservation pool has a surface area of about 24 ha and a maximum depth of approximately 1 m.

Although 90% of the game fish caught by anglers are planted rainbow trout, the annual reduction in water level, high summer water temperatures, and high alkalinity impose a great stress on the reservoir's game and pan fish. The natural habitats conducive to fish survival are adequate when the reservoir is at its maximum pool level, but are grossly inadequate when the irrigation drawdown takes place. Artificial habitat has been constructed from rocks, old tires, logs, brush, and straw to supply the fish with places for spawning, foraging, and hiding. With the start of June the reservoir is dominated by water skiers and boating enthusiasts.

10. Lake Meredith Reservoir (0810)

Lake Meredith Reservoir is situated in Crowley County near Sugar City. It has a surface area of 1,303 ha and a maximum depth of 4.6 m. The major stream feeding the reservoir is Lake Meredith Reservoir Inlet.

11. Milton Reservoir (0811)

Milton Reservoir is located in Weld County. It has a maximum surface area of 841 ha and a maximum depth of 12.2 m. The minimum conservation pool has a depth of about 6 m.

12. Shadow Mountain Reservoir (0813)

Shadow Mountain Reservoir, located in Grand County, has a surface area of 548 ha and a maximum depth of 11 m. It is part of the Colorado-Big Thompson Project and under the jurisdiction of the U.S. Bureau of Reclamation. Shadow Mountain Reservoir and Grand Lake (0807) are operated as one unit by the Bureau. The natural flow of water is from Grand Lake to Shadow Mountain Reservoir and then to Lake Granby, which serves as a major storage facility. When the need arises, Lake Granby water is pumped back to the Shadow Mountain Reservoir where it seeks an equilibrium level with Grand Lake. Water can leave Grand Lake via an outlet at its west end and pass under the continental divide through the Adams Tunnel, emerging on the east slope of the Rocky Mountains.

The geographic distribution and Landsat coverage of the study lakes are depicted in Figure 1-2. The water bodies, as viewed from Landsat orbital altitudes, are shown in Figures 1-3 through 1-5.

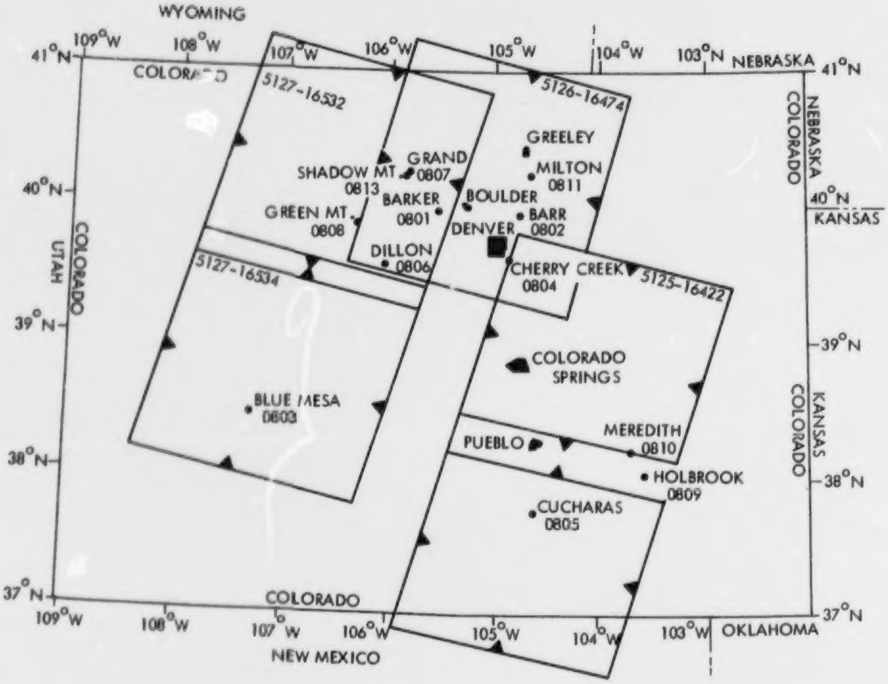
WYOMING
41°N
109°W
108°W
107°W
106°W
105°W
104°W
103°N
NEBRASKA
41°N
COLORADO
5127-16532
5126-16474
COLORADO
NEBRASKA
GREELEY
SHADOW MT.
0813
GRAND
0807
MILTON
0811
40°N
GREEN MT.
0808
BARKER
0801
BOULDER
BARR
0802
40°N
KANSAS
DENVER
COLORADO
UTAH
DILLON
0806
5127-16534
CHERRY CREEK
0804
5125-16422
39°N
39°N
COLORADO
SPRINGS
BLUE MESA
0803
KANSAS
COLORADO
MEREDITH
0810
PUEBLO
38°N
HOLBROOK
0809
38°N
CUCHARAS
0805
37°N
COLORADO
37°N
109°W
108°W
107°W
106°W
105°W
104°W
103°W
OKLAHOMA
NEW MEXICO

Figure 1-2. Landsat-1 Coverage of NES-Sampled Lakes for August 22-24, 1975. Scene 5125-16422 and the unnumbered scene were not processed because of excessive cloud cover

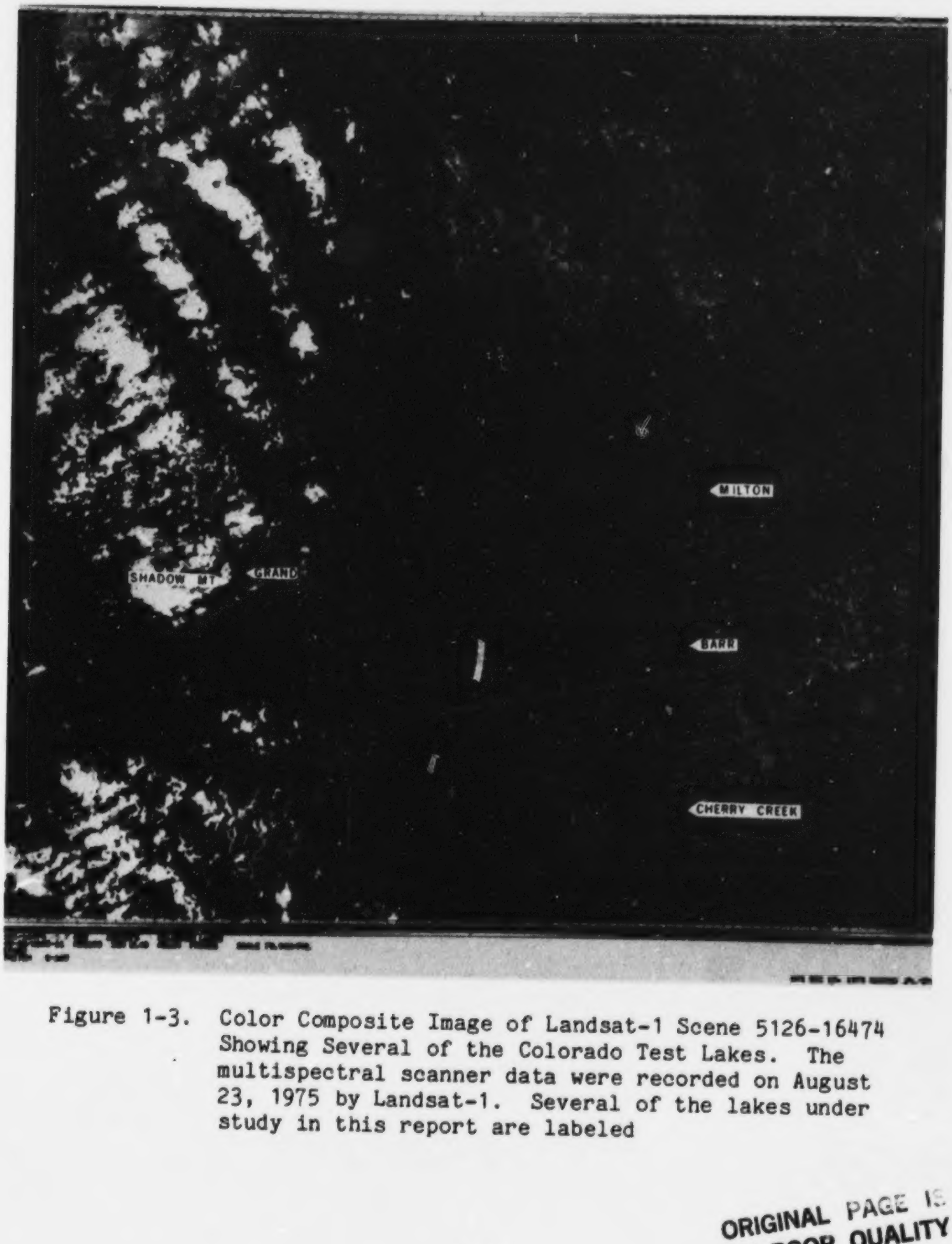
MILTON
SHADOW MT
GRAND
BARR
CHERRY CREEK

Figure 1-3. Color Composite Image of Landsat-1 Scene 5126-16474 Showing Several of the Colorado Test Lakes. The multispectral scanner data were recorded on August 23, 1975 by Landsat-1. Several of the lakes under study in this report are labeled

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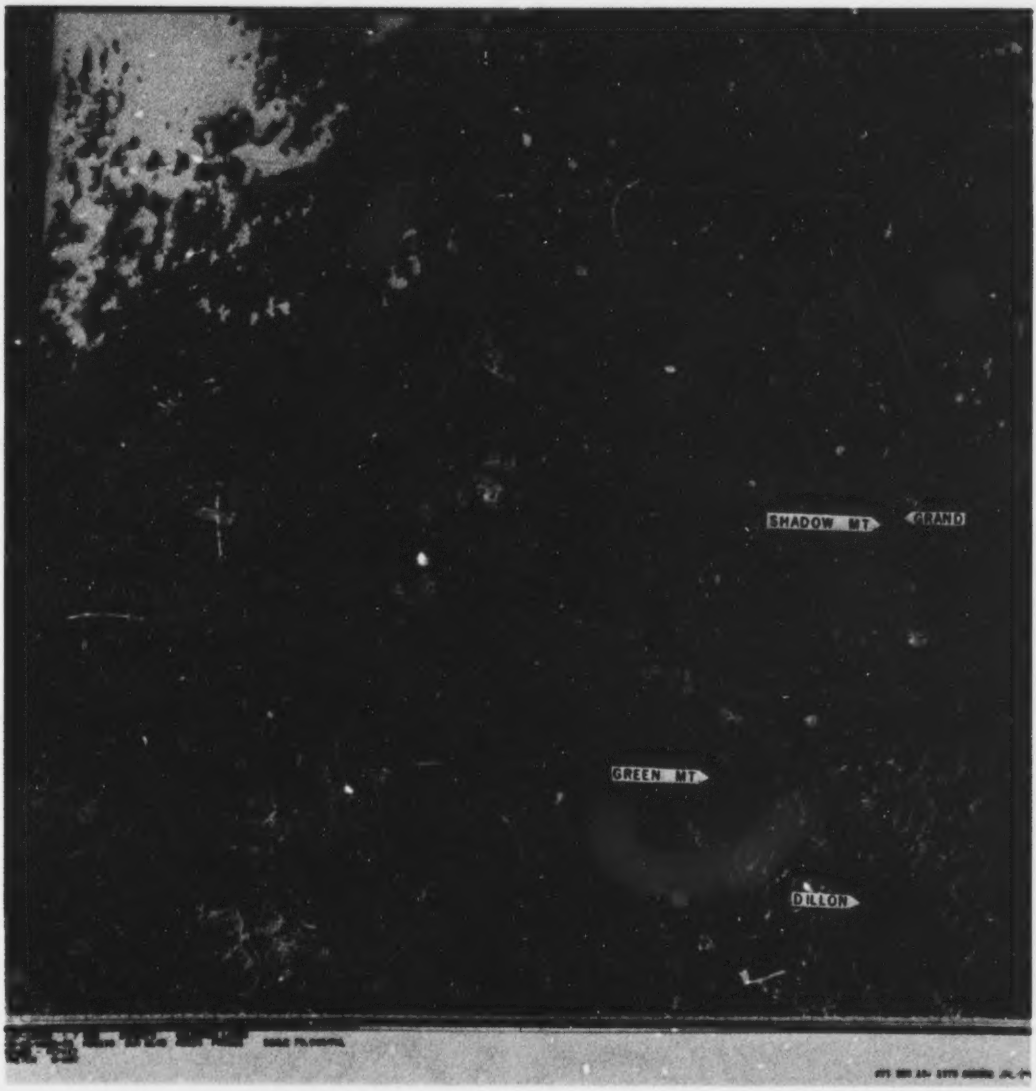
SHADOW MT
GRAND
GREEN MT
DILLON

Figure 1-4. Color Composite Image of Landsat-1 Scene 5127-16532 Showing Several of the Colorado Test Lakes. The multispectral scanner data were recorded on August 24, 1975 by Landsat-1. Several of the lakes under study in this report are labeled

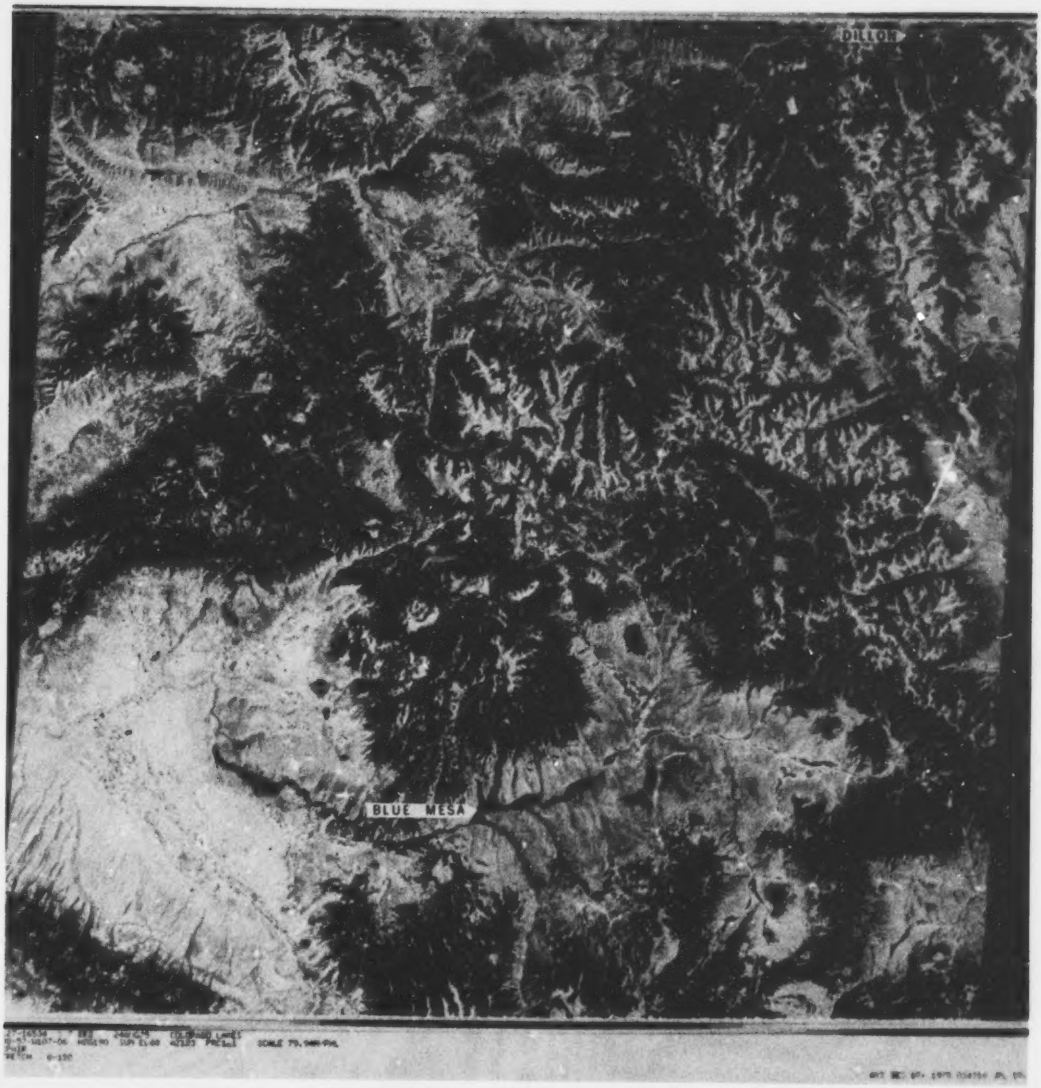

Figure 1-5. Color Composite Image of Landsat-1 Scene 5127-16534 Showing Several of the Colorado Test Lakes. The multispectral scanner data were recorded on August 24, 1975 by Landsat-1. Several of the lakes under study in this report are labeled

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SECTION II

BACKGROUND

In this section a number of concepts relating to lakes, the processes of eutrophication and succession, peripheral effects, and remote sensing are discussed. In addition, an overview of two remote sensing systems is presented. Detailed discussion on specific points are found in the publications cited.

A. LACUSTRINE CONCEPTS

There is far from universal agreement as to what constitutes a lake. Veatch and Humphrys (1966) suggested that to give the word "lake" a precise, limited meaning would probably be an exercise in futility because the word has been in use for a long time and been given a diversity of applications. The word is used as a synonym for pond, reservoir, and sea. It has been applied to bodies of fresh water and saline water; to standing water and widenings in rivers; to bodies of water measuring less than a hectare and to those gauged in hundreds of thousands of hectares; to naturally occurring water bodies and man-made reservoirs; to water-filled or partially filled basins; and to basins void of water. "Lake" is generally more prestigious than other common names (*e.g.*, pond, slough, reservoir) and is preferred by promoters of waterbased tourist and recreational businesses and commercial developers of shoreline property (Veatch and Humphrys 1966). Nevertheless, numerous attempts have been made to define and delimit the members of lentic series (*i.e.*, lake, pond, marsh, and their intergrades).

Forel defined a lake as a body of standing water occupying a basin and lacking continuity with the sea, and a pond as a lake of slight depth (Welch 1952). Welch (1952: 15-16) defined a lake as a "...body of standing water completely isolated from the sea and having an area of open, relatively deep water sufficiently large to produce somewhere on its periphery *a barren, wave-swept shore*." He employed the term "pond" "...for that class of very small, very shallow bodies of standing water in which quiet water and extensive occupancy by higher aquatic plants are common characteristics"...and suggested that all larger bodies of standing water be referred to as lakes. Zumberge (1952) defined a lake as an inland basin filled with water. Harding (1942) described lakes as "...bodies of water filling depressions in the earth's surface." In this report no deliberate effort will be made to carefully distinguish a lake from another lentic body on the basis of a definition. For example, an artificial reservoir may be called a lake or, at times, a water body.

1. Lake Succession

Lakes, although giving the impression of permanence when measured on the scale of the human life span, are transitory features of the earth's surface. All lakes, regardless of their origin, pass through the process of ecological succession which ultimately results in a terrestrial environment. The ephemeral nature of lakes is a consequence of two fundamental processes, the downcutting of the outlet and, more importantly, the deposition of allochthonous (arising in another biotope) and autochthonous (arising in the biotope under consideration) materials in the basin.

Generally speaking, most lakes commence the successional process as bodies possessing relatively low concentrations of nutrients and, generally, low levels of productivity.[2] The importation and deposition of materials (e.g., sediment) from the shoreline and the surrounding watershed gradually decreases the lake depth. The addition of allochthonous materials normally enriches the water and thereby stimulates the production of organic materials. Autochthonous materials increase the sedimentation rate, thus accelerating succession. Marked floral and faunal changes occur. Algal blooms become more common along with submergent and, eventually, emergent aquatic macrophytes. Desirable game fish may be replaced by less desirable species, the so-called "rough fish." When the successional process is not disrupted by major geologic or climatic changes, a lake eventually becomes a marsh or swamp which, in turn, terminates as dry land.

Lindeman (1942) stressed the productivity aspects in relation to lake succession. Figure 2-1 represents the probable successional productivity relationships for a hypothetical hydrosere (an ecological sere originating in an aquatic habitat) developing from a moderately deep lake located in a fertile humid continental region. Productivity is initially low, a consequence of low nutrient levels, but increases rapidly as nutrients become more available. The length of time required for completion of the successional process is a function of several factors including lake basin morphology, climate, and the rate of influx and nutrient value of allochthonous materials. It is readily apparent that allochthonous nutrients can drastically increase lake productivity and thereby shorten the life span of a lake.

2. Eutrophication

The word eutrophication is often used to denote the process whereby a pristine water body (e.g., lake) is transformed into one characterized by dense algal scums and obnoxious odors. Thick beds of aquatic macrophytes may become common. However, the word has been applied differently, according to the respective interests of its users. Weber (1907) used the German adjectival form of eutrophication "nahrstoffreichere" (eutrophe) to describe the high concentration of elements requisite for initiating the floral sequence in German peat bogs (Hutchinson 1973: 269). The leaching of nutrients from the developing bog resulted in a condition of "mitterlreiche" (mesotrophe) and eventually "nahrstoffearme" (oligotrophe). Naumann (1919) applied the words oligotrophic (under-fed), mesotrophic, and eutrophic (well-fed) to describe the nutrient levels (calcium, phosphorus, combined nitrogen) of water contained in springs, streams, lakes, and bogs (Hutchinson 1973: 269).

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[2] Edmondson (1974) suggested that the idea that all lakes are born oligotrophic and gradually become eutrophic as they age, is an old misconception.

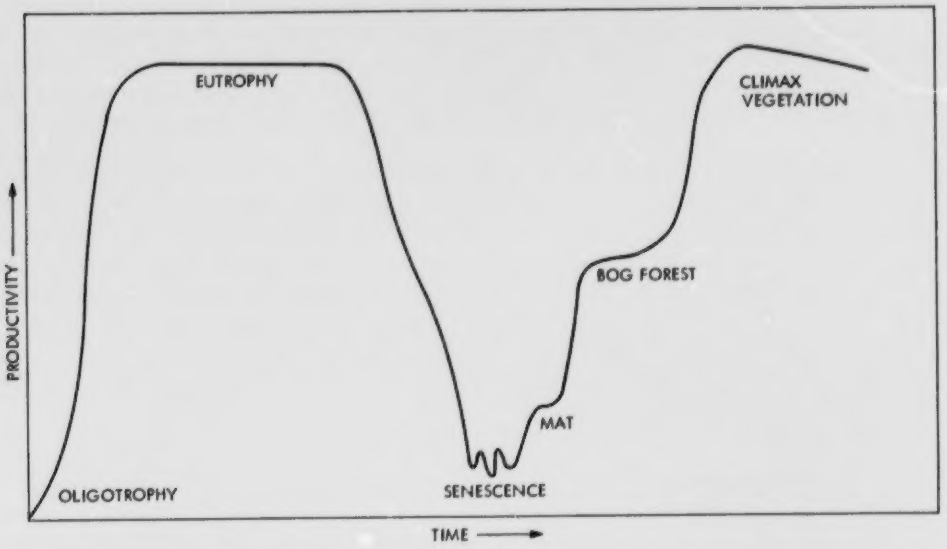

Figure 2-1. Hypothetical Productivity Growth-Curve of a Hydrosere. Lindeman (1942: 413) describes the curve as representing a hydrosere "...developing from a moderately deep lake in a fertile cold temperate climatic condition." It must be kept in mind that this is a generalized curve and not all lakes will follow it in total. For example, lakes that are light-limited because of suspended inorganic materials may never experience the initial dramatic increase in productivity. Adapted from Lindeman (1942: 413)

Naumann (1931) defined eutrophication as the increase of nutritive substances, especially phosphorus and nitrogen, in a lake. Hasler (1947) broadly interpreted eutrophication as the "Enrichment of water, be it intentional or unintentional..." Fruh, et al. (1966: 1237) defined the word as the "enhancement of nutrients in natural water..." while Edmondson (1974) suggested that many limnologists seem to use the term to describe "...an increase in the rate of nutrient input..." Hasler and Ingersoll (1968: 9) suggested that eutrophication is the "...process of enrichment and aging undergone by bodies of fresh water..." Vollenweider (1968) summarized the eutrophication of waters as meaning "...their enrichment in nutrients and the ensuring progressive deterioration of their quality, especially lakes, due to the luxuriant growth of plants with its repercussions on the overall metabolism of the water affected..." A search of the literature on eutrophication indicates that the meaning of the term, originally limited to the concept of changing nutrient levels, has been gradually expanded to include the consequences of nutrient enrichment.

Eutrophication occurs both naturally and as a result of man's activities (cultural or anthropogenic eutrophication). Many of man's practices relating to land use and to the disposition of municipal sewage and industrial wastes impose relatively large nutrient loadings on many lakes and rivers. In many cases, the enrichment results in algal blooms and other symptoms of eutrophication. The consequences of man-induced eutrophication often make the water body less attractive to potential users. More importantly, at least when a long-range viewpoint is adopted, eutrophication accelerates lake succession, thus shortening the time period before a lake loses its identity.

A comment regarding eutrophication is in order. The term, in the popular press and the mind of the layman, is being equated with a "bad" or highly undesirable situation. Certainly, when the enrichment levels reach extremes and undesirable manifestations occur (e.g., algal blooms, fish kills, obnoxious odors), the water body loses much of its value as a natural resource. However, enrichment of natural waters can result in increased primary productivity, leading to a larger biomass of consumers; eutrophic water bodies often provide excellent fishing opportunities.

The lakes of Colorado are undergoing the successional process and eutrophication. In general, the successional and enrichment processes are slow-moving in lentic bodies located in high mountain areas which are far removed from human activities. On the other hand, lakes and reservoirs which are located near metropolitan centers and in regions of intense agricultural activity are subjected to processes which can have serious consequences (i.e., degradation of water quality). The water quality in Colorado's lakes and streams is appreciably affected by the dissolved and suspended matter carried by runoff from the land surface.

Agricultural runoff and soil erosion are two nonpoint sources which affect the water quality of Colorado's lakes and streams. Other major nonpoint sources (of a more localized nature) which affect water quality include active and abandoned coal mines, intensive livestock and specialized agricultural operations, and storm drainage from urbanized area and construction sites. Agricultural runoff and runoff from ordinary precipitation events contain many contaminants (e.g., organic materials which are oxygen-demanding, minerals derived from the soil or applied by man, fecal coliforms, pesticides, herbicides, fertilizers, and other chemicals) from ground surface and ground cover which have accumulated through natural processes and nonintensive land husbandry. When rainfall of sufficient intensity occurs, soil erosion results. The severity and frequency of soil erosion are functions of many factors including intensity of immediate rainfall, prior climatic conditions, soil cover, soil texture, topography, and antecedent human activities. The eroded soil contributes both dissolved and suspended matter to the flowing waters. The suspended materials contributed by agricultural runoff and erosion are deposited in stream and lake beds. The deposited soil can bury aquatic life, create an oxygen demand, and release nutrients and chemicals to the flowing stream or overlying lake water. The influx of nutrients to a lake, assuming they are not deposited on the bottom and overlain by other materials, tend to make the water body more eutrophic. The accumulation of materials on the lake or reservoir bottom decreases the water depth and moves the water body closer to the point in time when its identity as a lake or reservoir is lost.

B. OPTICAL PROPERTIES OF PURE[3] AND NATURAL WATERS

It is readily apparent, even to the casual observer, particularly if looking downward from an aircraft, that lakes differ in color and brightness. Many investigations have been undertaken to develop a comprehension of the processes which result in the observed phenomena. Although a detailed discussion of the interaction of electromagnetic energy with the components of the hydrosphere and atmosphere is outside the scope of this report, a brief survey is essential to gain some understanding of the principles which both permit and yet constrain the use of remote sensing techniques in lake classificatory work.

The interaction between electromagnetic energy and chemically pure water has been studied by numerous investigators (e.g., Ewan 1894, Sawyer 1931, Collins 1925, James and Birge 1938, Hulburt 1945, Raman 1922, Dawson and Hulburt 1937). The transmission of electromagnetic energy through a material medium is always accompanied by the loss of some radiant energy by absorption. Some of the energy is transformed into other forms (e.g., heat, chemical) or to some longer wavelength of radiation (James and Birge 1938). Pure water is very transparent to violet, blue, and green light. In the infrared region, the extinction coefficient is high with a complementary low degree of transmission (see Hutchinson 1957: 381-383). The absorption spectral characteristics of pure water can be modified greatly through the addition of dissolved and particulate materials.

The absorption spectra of natural water (e.g., lake and ocean) have been studied in detail by Jerlov (1968), Duntley (1963), Atkins and Poole (1952), Birge and Juday (1929, 1930, 1932), and Juday and Birge (1933), to mention a few. Hutchinson (1957) has summarized the more important attempts to elucidate the interactions of light with natural waters, particularly in regard to lakes.

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[3] Water which is totally free of dissolved and particulate substances.

An electromagnetic wave impinging on the surface of a lake decomposes into two waves, one of which is refracted, proceeding into the aquatic medium, and a second wave which is reflected back to the atmosphere (Jerlov 1968). The wave entering the water is refracted as it passes through the air-water interface according to Snell's law, which may be expressed as:

$$n = \sin(i)/\sin(r)$$

where (i) is the angle of incidence, (r) is the angle of refraction, and (n) is the refractive index, which for water is approximately 1.33.

Most of the electromagnetic energy entering a lake is attenuated through the process of absorption. Although only a small percentage (less than 3 percent, Davis 1941) of the incident energy is backscattered from the lake water volume, this light (volume reflectance) is the focus of interest in remote sensing of water quality investigations. Its spectral characteristics have been shaped by the materials found in the lake's waters (dissolved and suspended materials, plankton, aquatic macrophytes, and air bubbles) and, in some cases, by bottom effects.

The attenuation of electromagnetic radiation in lake waters is a consequence of the relatively unselective effect of suspended particulate materials and the highly selective effect of dissolved coloring matter, usually of organic origin, on the electromagnetic spectrum. The dissolved matter absorbs strongly in the violet and blue wavelengths, moderately in the middle wavelengths (e.g., green), and much less strongly at longer wavelengths (Hutchinson 1957: 423). When the dissolved materials are present in small quantities, the water will be most transmissive in the green wavelengths. Lake waters with large amounts of dissolved substance are more transmissive in the orange and red wavelengths than in shorter wavelengths. However, the transmission of the red and orange light is still greater in pure water than in water containing particulate and/or dissolved materials. As water transparency diminishes, the detectable electromagnetic energy will be of progressively longer wavelength, at increasingly shallower depths (Hutchinson 1957: 424).

The color of a lake is the color of the electromagnetic energy backscattered from the lake body to the sensor. Lake color ranges from the blue of pure water through greenish blue, bluish green, pure green, yellowish green, greenish yellow, yellow, yellow brown, and clear brown (Hutchinson 1957: 415). Lake color need not be, and is usually not, the same as the lake water.[4] Lakes which are blue in color lack appreciable quantities of humic materials and colored materials in suspension (e.g., phytoplankton). The bluer the lake color, the smaller the amount of free-floating organisms contained in the water (Ruttner 1963: 21). Waters with a high plankton content possess a characteristic yellow-green to yellow color. The characteristic color may not be apparent owing to masking by other materials (e.g., suspended sediments). Ruttner (1963: 104) suggested that

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[4] Welch (1952: 84) defines water color as "...those hues which are inherent within the water itself, resulting from coloidal substances or substances in solution" (i.e., true color).

> A lake with very transparent and dark blue, blue-green, or green water is always oligotrophic. On the other hand, eutrophic lakes always have a relatively low transparency and are yellow-green to yellow-brown in color; but the determination of these optical properties alone will not establish the productivity type, for the turbidity can be of inorganic origin, and the color can come from humic substances.

Seston color, attributable to the reflection spectra of suspensoids of microscopic or submicroscopic size, is often observed in highly productive lakes. Lakes containing large quantities of suspended inorganic matter (e.g., silt) may acquire a characteristic seston color. However, in most cases the color is related to large concentrations of phytoplanktonic organisms (Hutchinson 1957: 417).

Scherz et al. (1969) have investigated the total reflectance (surface reflectance plus volume reflectance) curves of pure water and natural waters under laboratory conditions using a spectrophotometer. They reported that the addition of dissolved oxygen, nitrogen gases, and salts (e.g., NaCl, Na_2SO_4, $Na_3PO_4 \cdot H_2O$) had no apparent effect on the reflection curve. However, water from lakes in the Madison (Wisconsin) area had reflectance curves that differed both from the distilled water curve and from each other. These differences can be attributed to the presence of different algal organisms, since filtration of the lake waters produced similar reflectance curves, though different from that of pure water (Figure 2-2).

The color of natural waters is the end result of optical processes that are both numerous and complex. It is relatively easy to detect differences in color within a lake and also among a population of lakes. It is, however, more difficult to attach physical, chemical, or biological significance to the color, particularly when quantitative estimates are desired. The difficulty is compounded in waters having more than one class of particulates present, which is normally the case in natural water (McCluney 1976: 3-4).

The degree of success in sensing and interpreting the significance of color is partially a function of the sensor type employed for the collection of spectral data. We will now turn our attention briefly to the two remote sensing systems used in this project.

C. REMOTE SENSING SYSTEMS

Most attempts to classify or ordinate lakes employ contact sensing techniques coupled with the observations of the field crew to document the characteristics of the water bodies. The major constraints of most classification systems are the necessity of elaborate field data, difficulties in obtaining data for all lakes within a comparable time period or under similar circumstances, and lack of sufficient or appropriate

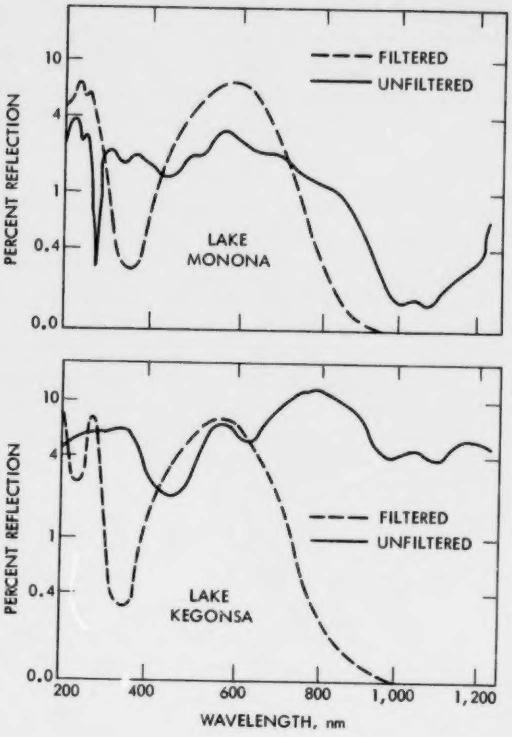

Figure 2-2. Reflection Characteristics of Filtered and Unfiltered Water Samples from Two Wisconsin Lakes in the Area of Madison. Adapted from Scherz *et al*. (1969)

sample locations to characterize the entire lake. A good historical data base for most of the lakes in the United States is either not available or is not suited to the development of an overall lake classification system. Efforts to characterize large numbers of lakes employing only contact-sensed data and field observations have limited usefulness since the data base was not intensively collected within a short time period and some of the data relied upon subjective observations of field personnel. It appears that satellite-borne sensors, such as the multispectral scanner carried by Landsat-1 and Landsat-2, and aircraft-borne sensors (e.g., modular multispectral scanner, MMS) have the capability to collect data of value for lake classification and monitoring activities.

The Landsat space observatories are attractive because they provide (1) repetitive coverage, (2) a synoptic view, and (3) a permanent record. The Landsat capabilities offer a unique opportunity to obtain a data base which could group the lakes into categories according to their spectral responses and also provide the opportunity to study relationships between certain trophic indicators and the spectral data with an eye toward the development of predictive models. Landsat provides what may be an economically viable technique for collecting data for the entire area of each lake within a reasonable time period. In addition, the sensible physical and optical properties of the lake waters are measured objectively. In about 25 seconds the Landsat multispectral scanner collects data in four bands of the spectrum for an area of the earth covering about 34,225 square kilometers. In regions of the earth where lakes are very abundant, a typical Landsat scene may contain several hundred to more than a thousand inland water bodies. With two satellites in operation, and assuming cloud-free conditions, repetitive coverage is provided on a 9-day basis. Clearly, the satellite offers certain advantages over conventional contact-sensing techniques.

While presenting a much more restricted synoptic view than Landsat, and having their own unique shortcomings, aircraft-borne modular multispectral scanner (MMS) systems are also attractive data sources for lake monitoring and classification programs. They are capable of providing greater spatial and spectral resolution than the Landsat MSS. In addition, the opportunity exists, at least in theory, to collect data more frequently because the aircraft can be scheduled to take advantage of cloud-free days. Landsat is locked into a predetermined 18-day (ignoring side overlap) data acquisition cycle; it cannot be moved into a particular area to take advantage of a cloud-free day. Rather its acquisition of lake data is of a more fortuitous nature. A more detailed examination of the two systems is presented below.

1. Landsat-1 System

Landsat-1 is one of three satellites NASA has orbited to survey and monitor the earth's natural resources (Figure 2-3). Both it and a companion, Landsat-2, were operational at the time the water truth data were collected from the Colorado Lakes. Landsat-1, however, provided coverage closer to the dates of water truth data acquisition than Landsat-2 and was therefore selected as the source of satellite-acquired multispectral scanner data.

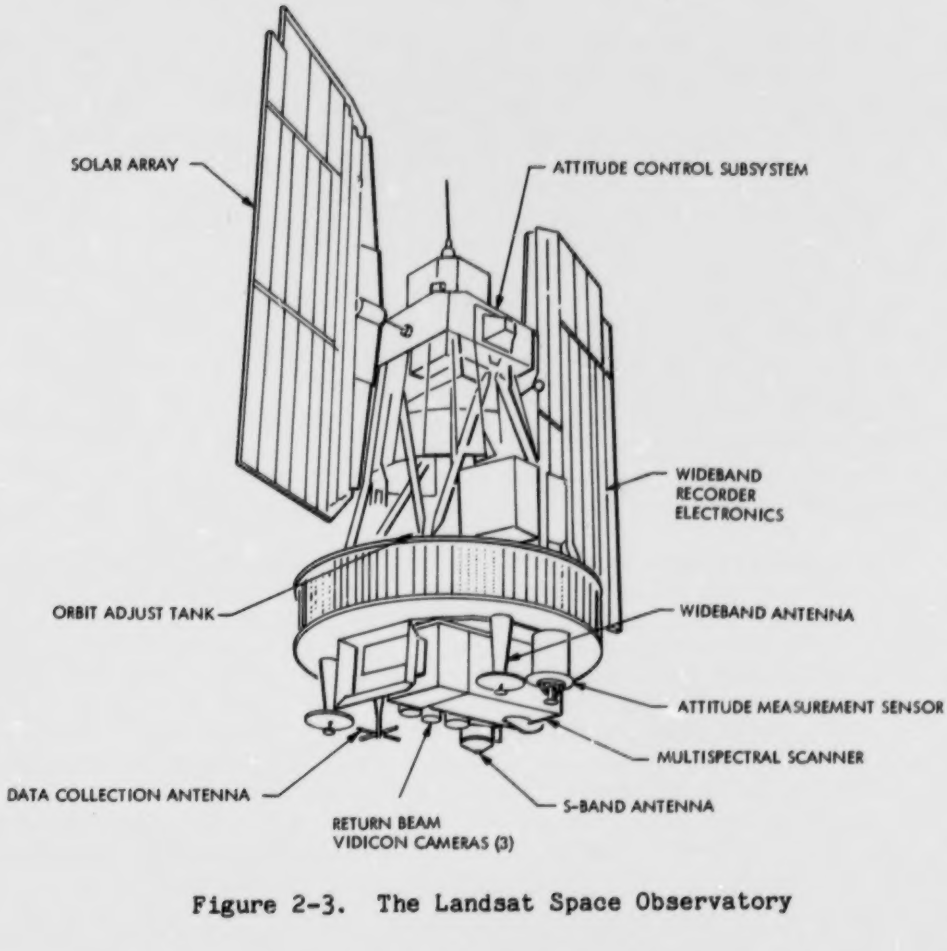
SOLAR ARRAY
ATTITUDE CONTROL SUBSYSTEM
WIDEBAND RECORDER ELECTRONICS
ORBIT ADJUST TANK
WIDEBAND ANTENNA
ATTITUDE MEASUREMENT SENSOR
MULTISPECTRAL SCANNER
DATA COLLECTION ANTENNA
S-BAND ANTENNA
RETURN BEAM VIDICON CAMERAS (3)

Figure 2-3. The Landsat Space Observatory

a. Landsat-1 Orbit Parameters and Earth Coverage. Landsat-1 was placed into a nominal sun-synchronous near-polar orbit by a Delta launch vehicle on July 23, 1972 (Freden 1973). Orbital parameters are listed in Table 2-1.

The earth coverage pattern is shown in Figure 2-4 for two orbits on two consecutive days. Orbital parameters result in a 1.43-deg westward migration of the daily coverage swath, equivalent to a distance of 159 km at the equator. The westward progression of the satellite revolutions continues, exposing all of the area between orbit N and orbit N+1 to the satellite sensors by day M. This constitutes one complete coverage cycle and consists of 251 revolutions. The cycle takes exactly 18 days and results in total global coverage between 81°N and 81°S latitude. Fourteen orbits (*i.e.*, revolutions) are completed during each of 17 days in a cycle with 13 revolutions during one day (NASA 1972). Approximately 188 scenes are acquired on an average day (Nordberg 1972).

b. Landsat-1 Instrumentation. The Landsat-1 payload consists of a return beam vidicon (RBV) camera subsystem, a multispectral scanner subsystem (MSS), and a data collection system (DCS). The RBV and MSS are designed to provide multispectral imagery of the earth beneath the observatory (*i.e.*, satellite). A malfunction occurred on August 6, 1972 (orbit 198), in the RBV power switching circuit, and the RBV cameras were turned off as only one sensor system can be used in conjunction with the one functioning video tape recorder. The second recorder aboard the observatory malfunctioned between orbits 148 and 181 (Freden 1973) necessitating data transmisison in a real time mode. The DCS serves to relay environmental information from geographically remote ground-based sensors to Landsat ground stations for processing and delivery to users. The RBV and DCS aspects of the satellite need not concern us.

Table 2-1. Landsat-1 Orbital Parameters[a]

Orbit Parameter	Actual Orbit
Semi-major axis, km	7285.82
Inclination, deg	99.114
Period, min	103.267
Eccentricity	0.0006
Time at descending node (a.m.) (southbound equatorial crossing)	9:42
Coverage cycle duration, days	18 (251 revolutions)
Distance between adjacent ground tracks (at equator), km	159.38

[a] Adapted from Data Users Handbook (NASA 1972)

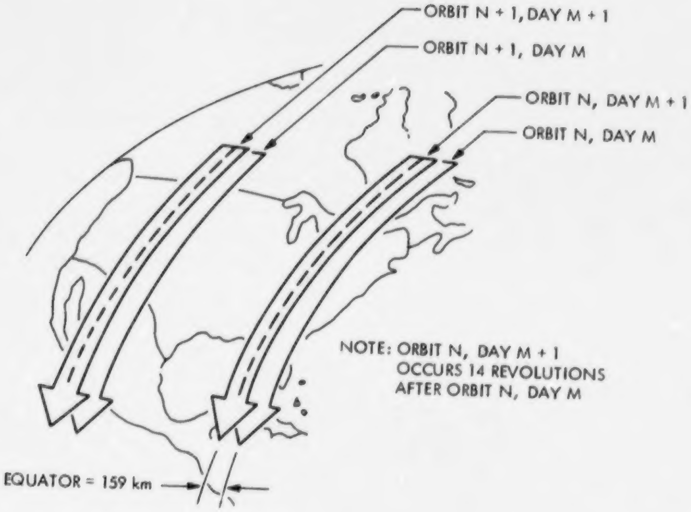
ORBIT N + 1, DAY M + 1
ORBIT N + 1, DAY M
ORBIT N, DAY M + 1
ORBIT N, DAY M
NOTE: ORBIT N, DAY M + 1 OCCURS 14 REVOLUTIONS AFTER ORBIT N, DAY M
EQUATOR = 159 km

Figure 2-4. Landsat-1 Ground Coverage Pattern. Adapted from Data Users Handbook (NASA 1972)

The MSS is a line-scanning radiometer which collects data by creating images of the earth's surface in four spectral bands simultaneously through the same optical system. The instrument operates in the solar-reflected spectral band region from 500 to 1,100 nanometers. Scanner characteristics are listed in Table 2-2. The MSS scans crosstrack swaths 185 km in width, simultaneously imaging six scan lines for each of the four bands. The object plane is scanned by an oscillating flat mirror positioned between the scene and a double reflector telescope-type of optical chain. An 11.5 deg (Horan, Schwartz, and Love 1974) cross-track field of view is produced by the mirror oscillating ±2.89 deg about its nominal position (Figure 2.5).

A nominal orbital velocity of 6.47 km/s, neglecting observatory perturbations and earth rotation effects, produces the requisite along-track scan. The subsatellite point moves 474 m along the track during the 73.42-ms active scan-retrace cycle which is itself a consequence of the 13.62-Hz mirror oscillation rate. The track distance of 474 m synchronizes with the 474 m along-track field of view of each set of six detectors. The line scanned by the first detector in one cycle of the active scan is in juxtaposition to the line scanned by the sixth detector of the previous scan (Figure 2-6).

Twenty-four glass optical fibers, arranged in a 4-by-6 matrix in the focused area of the telescope, intercept the light from the earth scene. Light impinging on the square input end of each optical fiber is conducted to an individual detector through an optical filter unique to the respective spectral band under consideration. Photomultiplier tubes (PMT) serve as detectors for Bands 4 through 6; Band 7 uses silicon photodiodes. A video signal is produced at the scanner electronics output as the image of a line across the swath is swept across the fiber during active scan. The signal is sampled at 9.95- s intervals, which correspond to a 56-m cross-track motion of the instantaneous field of view. The sampled signal is digitized and arranged into a serial digit data stream for transmission to ground stations. Individual signals are derived from light passing through each fiber, resulting in 24 channels of output.

The MSS, as found on Landsat-1 and Landsat-2, is a low-resolution device, both spatially and spectrally speaking. As can be seen in Table 2-2, three of the bands [green (GRN), red (RED), infrared-one (IR1)] are 100 nm in width with the infrared-two (IR2) band covering 300 nm. Figure 2-7 illustrates a generalized spectral reflectance curve for a single picture element (pixel - the MSS spatial resolution unit with nominal measurements of 57-by-79 m) of a hypothetical lake. The width of the MSS bands disallows the recording of the fine details in the curve. The MSS output more closely resembles Figure 2-8. Responses are given as values for the various wavelengths bands (*e.g.*, 500 to 600 nm, GRN) instead of specific values for the entire spectral range. This procedure crudely defines an entire range of wavelength responses as four single readings.

Table 2-2. Landsat-1 MSS Characteristics

Item	Characteristics			
Telescope optics	22 cm (aperture diameter), f/3.6 Ritchey-Chretien			
Scanning method	flat mirror oscillating ±2.9 deg at 13.62 Hz			
Scan (swath) width	11.5 deg (185 km at 917 km altitude)			
Scan duty cycle	44%			
Instantaneous field of view (IFOV)	86 μrad			
Number of bands	four			
Number of lines (detectors) scanned per band	six			
Limiting ground resolution from 917 km altitude	80 m			
Spectral band wavelength:				
NDPF band code				
Band 4 (green)	500-600 nm			
Band 5 (red)	600-700 nm			
Band 6 (near-infrared one)	700-800 nm			
Band 7 (near-infrared two)	800-1,100 nm			
Sensor response:	Band 4	Band 5	Band 6	Band 7
Detector	PMT[a]	PMT	PMT	Photodiode
Nominal input for 4-V scanner output (10^{-4}W cm^{-2}sr^{-1})	24.8	20.0	17.6	46.0
Scanner and multiplexer weight	50 kg			
Signal channels	24			
Telemetry channels	97			
Command capability	72			
Scanner size	Approximately 36 x 38 x 89 cm			

[a] Photomultiplier tube.

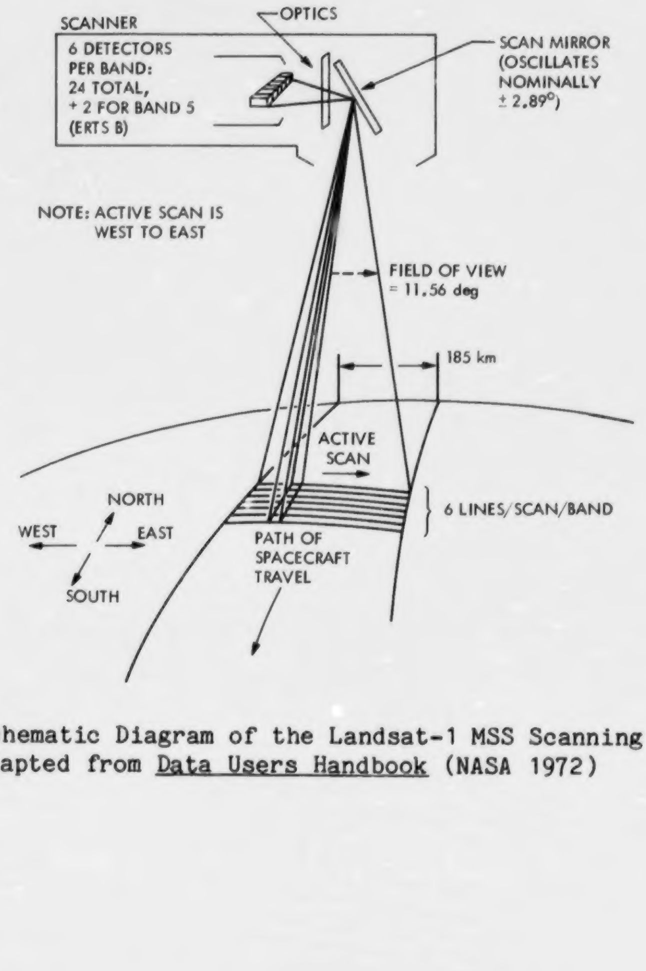
SCANNER
OPTICS
6 DETECTORS PER BAND: 24 TOTAL, + 2 FOR BAND 5 (ERTS B)
SCAN MIRROR (OSCILLATES NOMINALLY ± 2.89°)
NOTE: ACTIVE SCAN IS WEST TO EAST
FIELD OF VIEW = 11.56 deg
185 km
ACTIVE SCAN
6 LINES/SCAN/BAND
NORTH
WEST
EAST
SOUTH
PATH OF SPACECRAFT TRAVEL

Figure 2-5. Schematic Diagram of the Landsat-1 MSS Scanning Arrangement. Adapted from Data Users Handbook (NASA 1972)

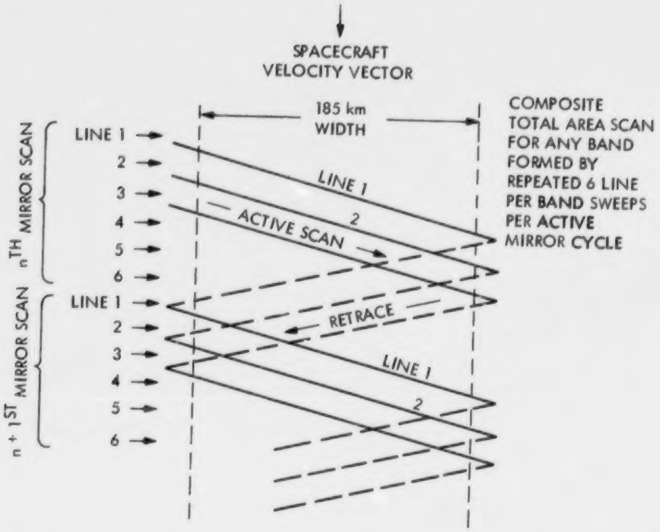
SPACECRAFT
VELOCITY VECTOR
185 km
WIDTH
COMPOSITE
TOTAL AREA SCAN
FOR ANY BAND
FORMED BY
REPEATED 6 LINE
PER BAND SWEEPS
PER ACTIVE
MIRROR CYCLE
n^TH MIRROR SCAN
LINE 1
2
3
4
5
6
LINE 1
2
ACTIVE SCAN
RETRACE
n + 1^ST MIRROR SCAN
LINE 1
2
3
4
5
6
LINE 1
2

Figure 2-6. Ground Scan Pattern for a Single MSS Detector.
Adapted from Data Users Handbook (NASA 1972)

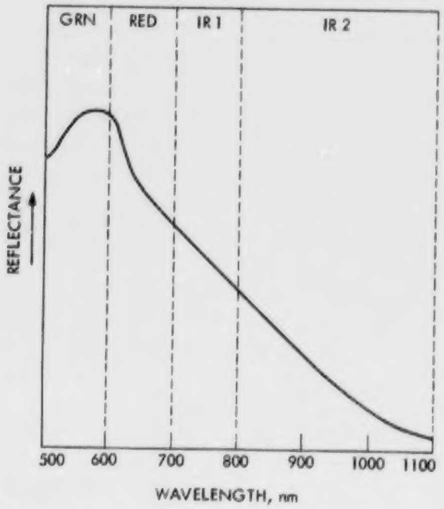

Figure 2-7. Generalized Spectral Reflectance Curve for a Single Picture Element (Pixel) of a Hypothetical Lake

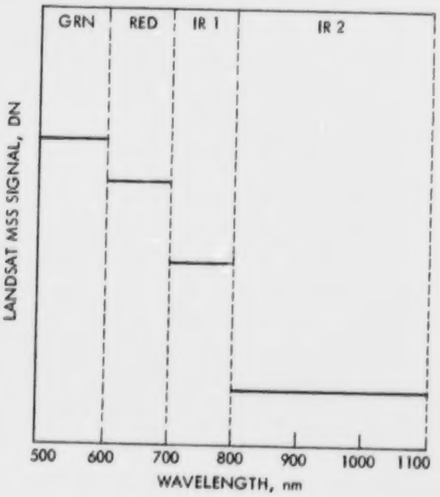

Figure 2-8. Generalized Output of the Landsat MSS in Response to the Spectral Distribution Illustrated in Figure 2-7

As mentioned above, the nominal MSS pixel measures 57 by 70 m, thereby covering an area of 0.3933 ha. Through the use of resampling techniques it is possible to adjust the pixel size (e.g., an 80-by-80-m pixel corresponding to 0.64 ha was employed in this study). It must be kept in mind that the MSS gathers energy over the area of its nominal pixel. Many measurements made using contact techniques are of the point type, a direct contrast to those acquired by the Landsat MSS. It is commonly recognized that some Landsat MSS pixels contain a mixture of water and land features. This normally occurs along the water-land interface or in situations where the water body is much smaller than the pixel or, conversely, where an island is much smaller than the pixel. The pixel size also tends to give small water bodies or those with very irregular shorelines a "blocky" appearance. A visual examination of imagery generated from the Landsat MSS will usually detect a pattern of stripes running orthogonal to the satellite's path. This is a consequence of an imbalance among the MSS's 24 detectors. The problem is particularly noticeable when work is in the digital domain (i.e., work is with the CCT's).

It should be kept in mind that, although the Landsat MSS was designed with the earth's resources in mind, it was not developed specifically for water. In fact, if anything, its design favors terrestrial features. Most of the incident solar energy entering a water body is attenuated through absorption. The volume reflectance of a water body is generally less than 3% of the incident light. Thus the energy reaching the MSS from water bodies is relatively small in magnitude compared to that received from most land features. While it is possible to increase the MSS's gain in the GRN and RED bands, this is not normally done.

2. Aircraft-Borne Modular Multispectral Scanner System (MMS)

The modular multispectral scanner system is an airborne, 11-channel scanning multiband radiometer designed to perform quantitative measurements of the electromagnetic radiation reflected or emitted from a ground scene. Table 2-3 lists the characteristics of this system.

The scanner is mounted in a bay on the underside of the aircraft and views the ground through an opening in the aircraft skin. A rotating wedge mirror is used to scan the ground below the aircraft perpendicular to the direction of flight. This allows a telescope assembly to focus an image of successive small areas of the ground onto an aperture called the primary aperture. Light passing through this aperture is split into 11 spectral bands (i.e., channels) by a spectrometer consisting of a combination of spectral filters and a diffraction grating. The images of the scene on the ground, observed in each wavelength band, are then focused onto separate detectors and are converted into electrical signals. Sequential line-by-line scans are generated by virtue of the forward motion of the aircraft. In order to compensate for changes in the velocity/altitude (V/H) ratio of the aircraft and maintain contiguous scanning along the flight path, the speed of the scan mirror may be varied from 10-100 scans/second by the sensor operator.

The instantaneous field-of-view (IFOV) provided by the field defining apertures and the telescope is 2.5 mrad. Basic registration of 0.1 IFOV is maintained between the thermal and the visible/near IR channels because of the use of a common optical system up to the beam splitter. The visible/near IR channels are inherently registered because the optical input to all those channels comes from the single spectrometer slit, and the registration of the thermal channel is maintained by a mechanical positioning of the thermal detector.

As evident from Table 2-3, the MMS channels (CH) or bands are considerably narrower than those of the Landsat MSS. This is very advantageous because it permits a more detailed examination of the spectral curve for areas or objects of interest. Figure 2-9 depicts the generalized output of the MMS in response to the spectral distribution illustrated in Figure 2-10. In this particular comparison, picture element (pixel) sizes are the same and atmospheric effects are assumed to be equal. You will note that the MMS has greater resolving power of the spectral distribution than does the Landsat MSS.

D. PERIPHERAL EFFECTS

The character of the electromagnetic energy impinging on both the MMS and Landsat-1 MSS has been shaped through interactions with numerous environmental phenomena (Figure 2-10). Some of the interactions are highly desirable because they alter the character of the light, which may then be interpreted in terms of some parameter of interest (e.g., Secchi depth). Other interactions of light energy with the environment may be detrimental to a particular study. It goes without saying that what may be a vitally important interaction in one study may be devastating in another.

The earth's atmosphere has a pronounced effect on the solar spectrum and on lake water color as sensed from aircraft and satellite altitudes. Atmospheric conditions (e.g., degree of cloudiness; presence of fog, smoke, and dust; amount of water vapor) affect the degree of insolation attenuation. Weather conditions strongly affect the distribution of energy between sunlight and skylight (Piech and Walker 1971: 186-187), contributing a degree of uncertainty in water quality assessment through remotely sensed color measurements. Hulstrom (1973: 370-376) has pointed out the adverse impact that cloud bright spots can have on remote sensing techniques which utilize reflected energy.

The degree of scattering and absorption imposed on the return signal from water bodies is related to atmospheric transmittance and can result in changes in lake color when sensed at aircraft high flight and satellite altitudes. The attenuated return signal is also contaminated by electromagnetic radiation from the air column (path radiance). Rogers and Peacock (1973) have reported that solar and atmospheric parameters have a serious adverse impact on the radiometric fidelity of Landsat-1 data. Path radiance was found to account for 50% or more of the signal received by the MSS when viewing water and some land masses. Even at aircraft altitudes, the atmosphere can have a substantial

Table 2-3. MMS System Specifications

Channel No.	Center Wavelength λc, μm	Spectral Bandwidth Δ, μm	Detector Type
1	0.410	0.06	Silicon
2	0.465	0.05	Silicon
3	0.515	0.05	Silicon
4	0.560	0.04	Silicon
5	0.600	0.04	Silicon
6	0.640	0.04	Silicon
7	0.680	0.04	Silicon
8	0.720	0.04	Silicon
9	0.910	0.10	Silicon
10	1.015	0.09	Silicon
11	-	8-14 (thermal)	Mercury Cadmium Telluride

Scan Speed	10 to 100 rps
V/H	continuously variable from 0.025 to 0.25 rad/s
IFOV	2.5 mrad
FOV	100 deg
Roll compensation	± 10 deg
Detectors	Silicon PIN diodes (channels 1 through 10) HgCdTe (channel 11)
Frequency response	DC to 200 kHz
% obscuration	18% of primary mirror area
Focal length	15 in. (.381 m)
Primary mirror diameter	4 in. (.0762 m) (3.6 in. unobscured)
Second mirror diameter	1.7 in. (0.04318 m)
Registration	0.1 IFOV for all channels including thermal channel
Scene video resolution elements per scan	802

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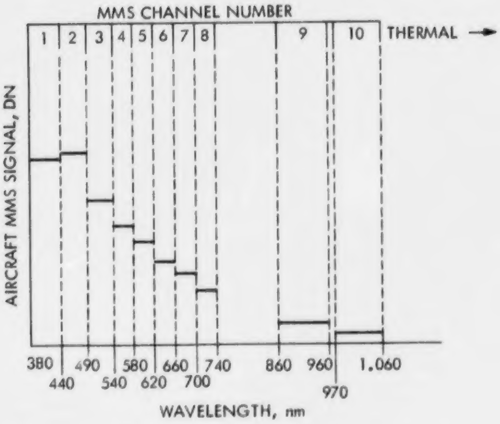

Figure 2-9. Generalized Output of the Aircraft-Borne MMS in Response to the Spectral Distribution Illustrated in Figure 2-10. Compare Figure 2-9 with Figure 2-8

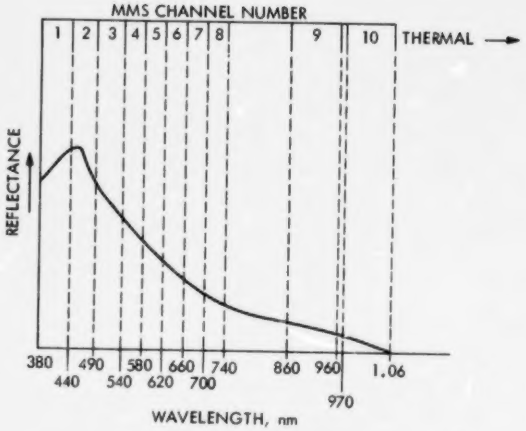

Figure 2-10. Generalized Spectral Reflectance Curve for a Single Picture Element (Pixel) of a Hypothetical Lake. The MMS Spectral Windows Are Superimposed on the Curve

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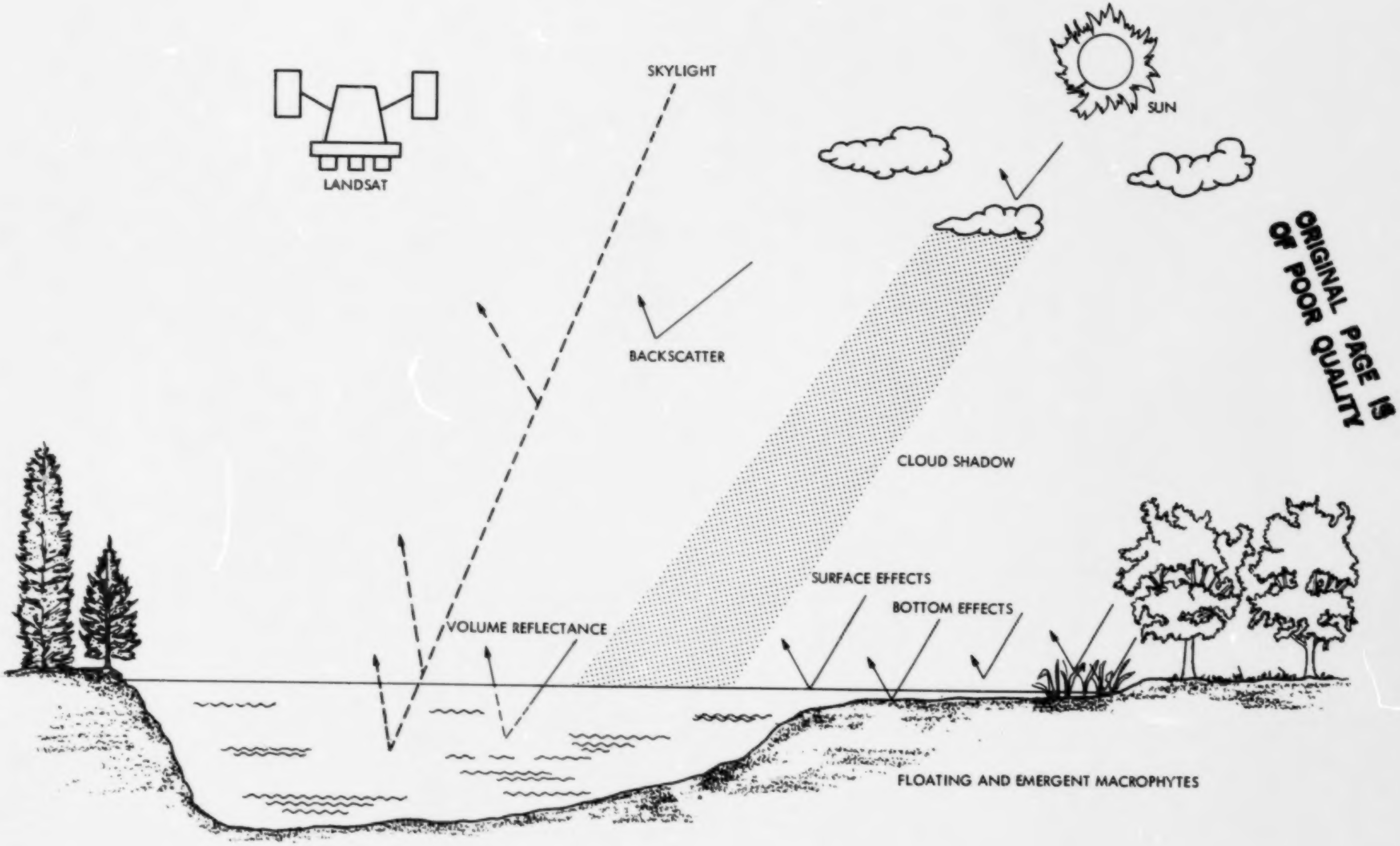
LANDSAT
SKYLIGHT
SUN
BACKSCATTER
CLOUD SHADOW
SURFACE EFFECTS
BOTTOM EFFECTS
VOLUME REFLECTANCE
FLOATING AND EMERGENT MACROPHYTES

Figure 2-11. Some Components and Interactions of Light with Hypothetical Lake and Atmosphere

impact on the character of electromagnetic energy reflected from the earth's surface. The magnitude of the adverse atmospheric effects can be reduced, though not completely eliminated, by using imagery or digital data collected on clear, cloudless days. This is the approach used in this investigation.

The Landsat-1 spacecraft passes over the same point on the earth at essentially the same local time every 18 days. However, even though the time of passover will remain essentially the same throughout the year, solar elevation angle changes cause variations in the lighting conditions under which the MSS data are obtained. The changes are due primarily to the north or south seasonal motion of the sun (NASA 1972). Changes in solar elevation angle produce changes in the average scene irradiance as seen by the sensor from space. The change in irradiance is influenced both by the change in the intrinsic reflectance of the ground scene and by the change in atmospheric backscatter (path radiance). The actual effect of changing solar elevation angle on a given scene is very dependent on the scene itself (NASA 1972). For example, the intrinsic reflectance of sand is significantly more sensitive to changing solar elevation angle than are most types of vegetation (NASA 1972). The effects of changing solar elevation angle are of particular importance when scenes taken under significantly different angles are compared. The use of color ratios in lieu of raw data values may be of value in reducing the magnitude of the solar-angle-induced effects by normalizing the brightness components. The approach is given some consideration in this study.

A portion of the radiation impinging on the lake surface will be reflected. The percentage of surface-reflected energy is a strong function of the angle of incidence. The light reflected from the water-atmosphere interface is composed of diffuse light from the sky (skylight) and specularly reflected sunlight. Specular reflection areas contained in a scene are of little value in most water studies, the possible exception being the determination of surface roughness. The specularly reflected radiation exceeds, by several orders of magnitude, the reflected energy emanating from beneath the water surface (Curran 1972: 1857). Specular reflection has not been demonstrated as being a major problem in water-related projects employing Landsat MSS data. This is probably largely because the MSS has a relatively small scan width or field of view (FOV) of 11.5 deg. On the other hand, the MMS has a FOV of 100 deg, which makes it very susceptible to specular reflection.

Surface reflected skylight, containing no water quality color information, can compose from 10% of the return signal on a clear day to 50% on a cloudy day (Piech and Walker 1971). The surface-related skylight not only increases the apparent reflectance from the water body (volume reflectance), but also affects the shape of the reflectance curve. Surface roughness is known to have an effect on the percentages of light reflected and refracted at the interface (Jerlov 1968). However, the effect of surface is negligible in estimating total radiation entering a water body when the solar elevation angle is greater than 15 deg (Hutchinson 1957: 375).

The lake bottom characteristics (color and composition) will also affect the intensity and/or the spectrum of the volume reflectance in settings where water transparency permits the reflection of a significant amount of radiation from the bottom materials. In studies involving the estimation of water depth or the mapping of bottom features, it is essential that the lake bottom be "seen" by the sensor. Bottom effects are capitalized upon and put to a beneficial use. However, in this investigation, bottom effects are considered to be an undesirable peripheral effect. A sensor with the capabilities of the Landsat MSS or the MMS is not able to "see" much deeper into a lake than Secchi depth. The Secchi transparency of the study lakes is, in most cases, relatively small when compared to the mean depth of each lake. The assumption is made, as a first approximation, that the bottom effect is relatively insignificant when considering each of the selected lakes as an entity.

It is evident that many factors influence the intensity and spectral characteristics of the electromagnetic radiation which is collected by the sensor. Absolute quantification of remotely sensed phenomena requires that all of the adverse effects be accounted for in the return signal. Failure to account for all of the variation introduced by the detrimental effects might be criticized as being simplistic or naive. However, given the present state of the art along with manpower, time, and monetary constraints a complete accounting is not possible.

E. REMOTE SENSING OF COLORADO LAKES

In this subsection an overview is presented by taking a "first look" at several Colorado lakes and reservoirs. Initially, the focus of attention will be directed toward several Landsat MSS images of Scene 5127-16534.

A visual examination of Landsat MSS imagery indicates that gray tone differences can be detected in the population of Colorado lakes. Figures 2-12 through 2-15 represent respectively, the IR2, IR1, RED, and GRN gray tone images of LANDSAT Scene 5126-16474. The IR2 image (Figure 2-12) clearly demonstrates a great contrast between water bodies and terrestrial features. Water is an excellent absorber of radiation wavelengths comprising the IR2 band and, hence, water bodies appear black. Figure 2-13, the scene's IR1 counterpart, exhibits a similar contrast between water and land. A careful examination of the water bodies suggests surface or near-surface phenomena in some lakes. Gray tone differences both within specific water bodies and among members of the lake population are most pronounced in the RED image (Figure 2-14). In this band, lakes with extremely turbid water often meld with the terrain features, a consequence of similar gray tone values. A vivid example of this occurring in Wisconsin lakes is presented in Boland (1976: 12-17). Though less obvious to the eye, gray tone differences are also noted among water bodies in the GRN band image (Figure 2-15).

When viewing LANDSAT scenes such as the black and white standard photographs produced by the EROS Data Center, it should be kept in mind that no special effort is made to enhance water bodies and related

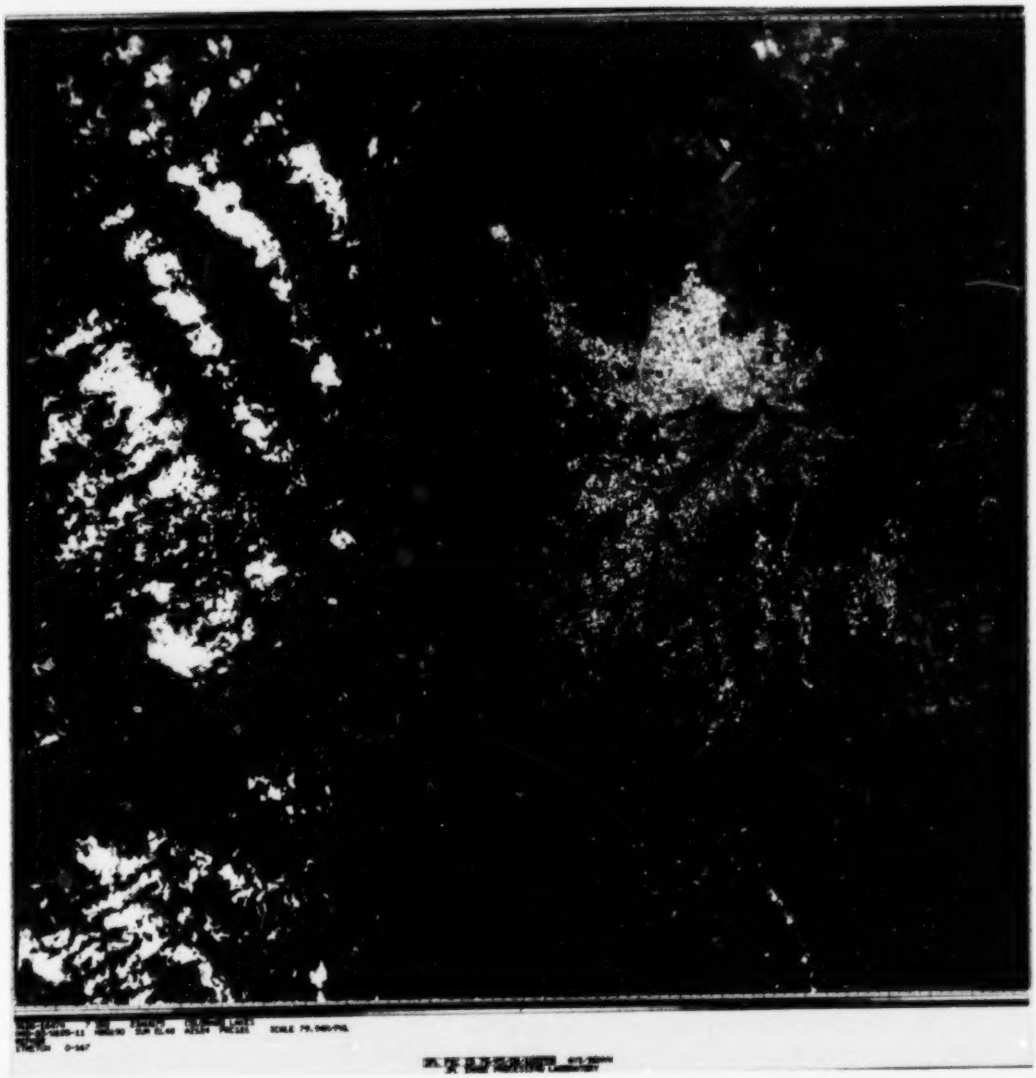

Figure 2-12. IR2 Image of Landsat Scene 5126-16474, August 23, 1975. The IR2 band (also called Band 7) is excellent for discriminating water from terrain

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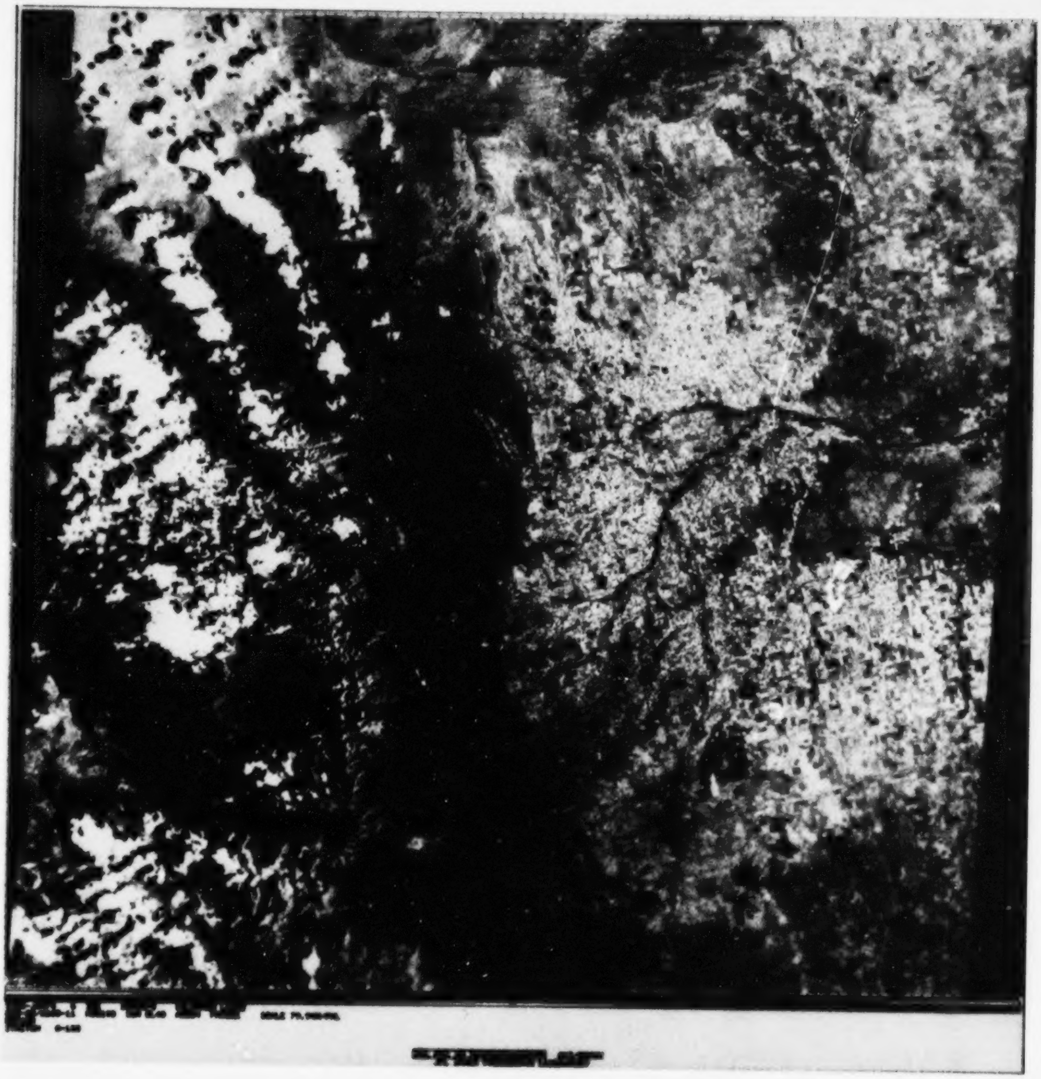

Figure 2-13. IR1 image of Landsat Scene 5126-16474, August 23, 1975. This band (also called Band 6) is excellent for discriminating water from terrain. Surface or near-surface phenomena are evident in some of the water bodies

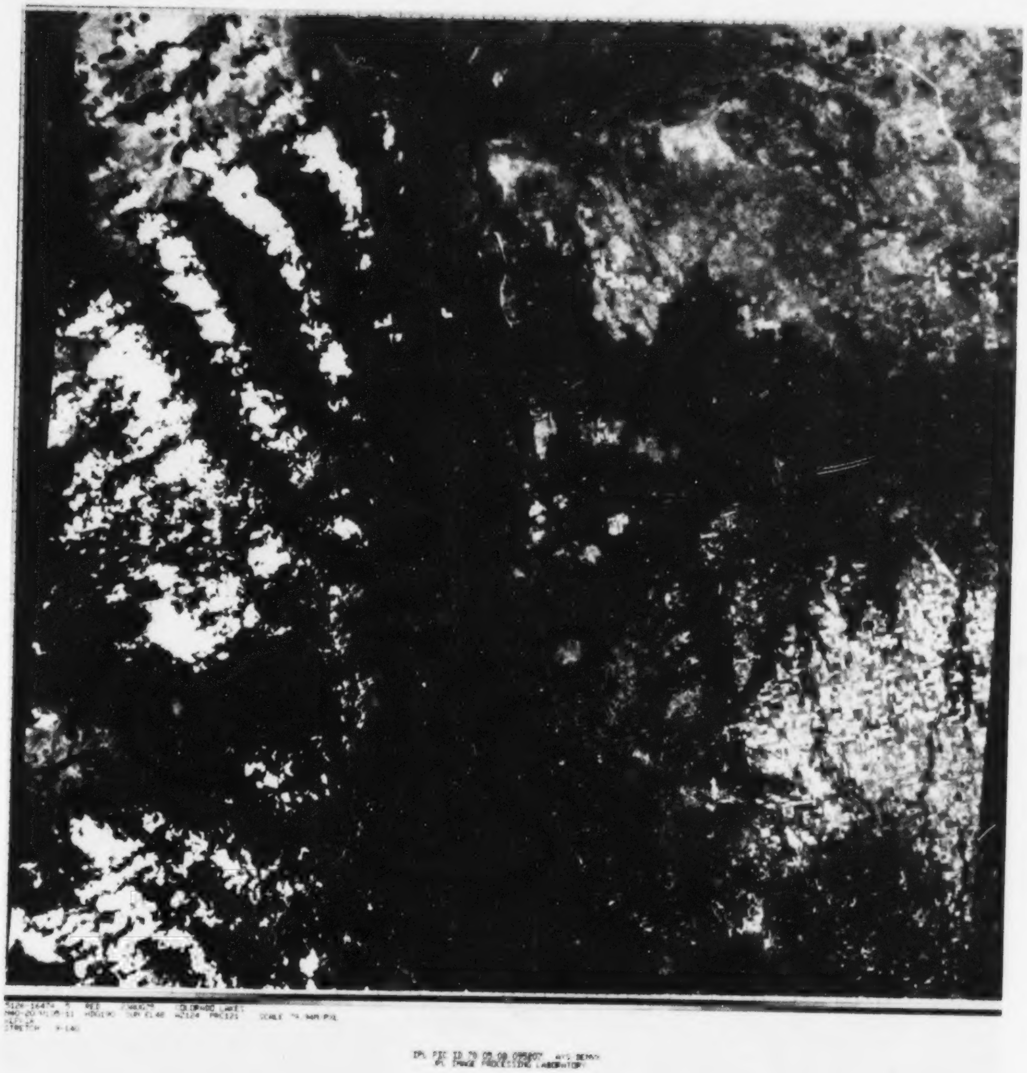
5126-16474
COLORADO LAKES
SCALE
STRETCH
JPL IMAGE PROCESSING LABORATORY

Figure 2-14. RED image of Landsat Scene 5126-16474 (August 23, 1975). The variations in water body gray tones suggest differences in water quality

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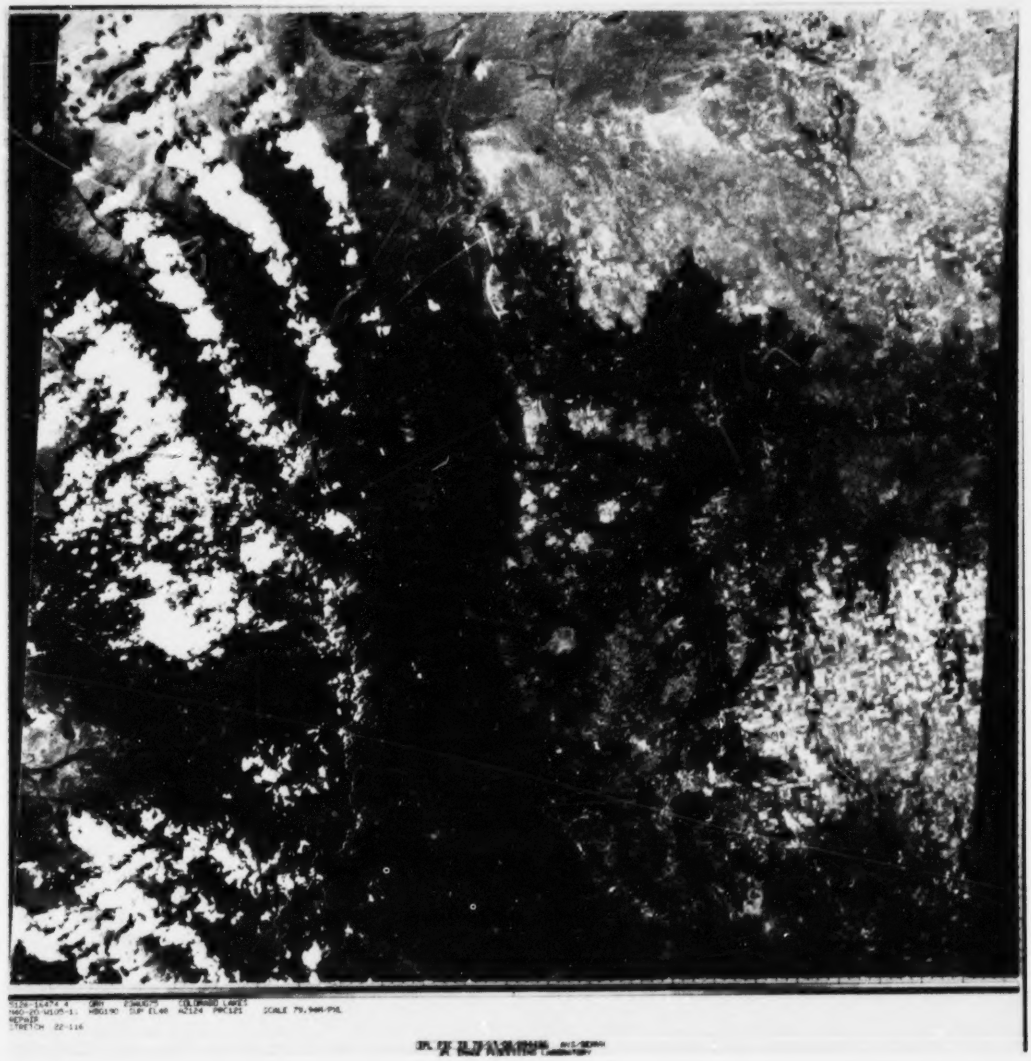
5126-16474 4 GRN 23AUG75 COLORADO LAKES
STRETCH 22-116

Figure 2-15. GRN Image of Landsat Scene 5126-16474 (August 23, 1975). While lacking in the contrast evident in the RED, IR1, and IR2 images of the scene, gray tone differences are still apparent among the water bodies. Compare with Figures 2-12, 2-13, and 2-14

phenomena. Indeed, a loss of spectral information occurs when the MSS digital data are transformed into photographic products. Specifically, the products have a relatively small density range compared to the sensitivity range of the MSS. This results in a scale compression when the MSS data are transformed into a film image on an electron beam recorder. In addition, the range of energy returns from water bodies is small and concentrated at the lower end of the MSS intensity scale. Scale compression coupled with the small range of digital number (DN) values adds to the difficulty of determining trophic state index and indicator values through visual and densitometric evaluation of "standard" EROS black and white photographs.

As can be seen from Figures 2-12 through 2-15, it is possible to detect spectral differences for Colorado lakes using Landsat imagery coupled with photointerpretive techniques. Spectral differences, exhibited as gray tone variations, are also evident in imagery generated from MMS data (examples of single-channel MMS imagery will not be shown here). The real challenge is one of relating the spectral variations to chemical, biological and physical phenomena measurable through contact-sensing techniques and/or acquired through ground level observation.

As indicated earlier, the quantity and spectral composition of radiation directed upward across the water-atmosphere interface is, in part, a function of the dissolved substances and particulate materials in the water. While water itself is capable of scattering and absorbing light, the major portion of the scattering is due to materials in the water. Scattering due to dissolved color is highly selective, while suspended solids tend to affect volume reflectance in a rather nonselective fashion. It then follows that increases in suspended particulate materials in lake water will tend to increase the reflectance in the Landsat bands and MMS channels. It should be noted that some natural waters will, at least for a portion of the spectrum, exhibit a lower volume reflectance than that of pure water. Humic waters have this characteristic as demonstrated by Rogers (1977: 3-85). None of the Colorado water bodies in this study fall in the humic category.

It has been well documented that the MSS and MMS are incapable of directly detecting substances such as nutrients (*e.g.*, phosphorus) in water. This does not mean, however, that it is impossible to get some estimate of such substances. Phosphorus, for example, is known to be a key element in primary productivity, stimulating the production of biomass. Differences in nutrient levels are often directly related to the magnitude of the manifestations of eutrophication (*e.g.*, turbidity, chlorophyll *a*, algal blooms). Such phenomena are sensible to the MSS and MMS. Again, it should be kept in mind that the energy return from natural water bodies is generally low compared to that of land features. Thus, all of the water quality related information is contained in a relatively small range of DN levels for each band or channel for the Colorado lakes. This precludes developing trophic indicator estimates having the accuracies and precisions of the contact-sensed data.

This project is based on the premise that the volume reflectances of water bodies represent distinct characterizations of their optical properties which are then interpretable in terms of parameters considered important in assessing the trophic state. This concept assumes:

(1) Waters with similar optical properties will yield similar spectral responses.

(2) Under identical light conditions, the volume reflectance as measured in all bands and channels will generally be lowest for clear water lakes. The inverse is also assumed.

(3) Detritus, phytoplankton, suspended solids and most other natural large particulates are Mie scatterers and, therefore, scatter approximately uniformly over the spectrum sensed by the sensors.

As the quantity of scattering materials increases, there is a relatively uniform increase in the reflectance curve (Piech and Walker 1971: 195). In other words, the reflectance curve will become higher and flatter as the water becomes more turbid.

(4) Substances (e.g., phosphorus) which are not directly detectable to the sensors can be sensed indirectly through their effects on parameters sensible to the sensors.

(5) Shifts in dominant color reflectance from the blue range toward the red-brown range reflect increases in lake productivity or associated increases in dissolved color or inorganic turbidity.

It should be recognized that the contact-sensed data for this project were collected as part of an ongoing national survey of lakes and reservoirs; little or no thought was given to the possibility of the data being used in a satellite-related project. Thus, some highly desirable parameters (e.g., total suspended solids, organic particulates, inorganic particulates) were not measured during the time of satellite flyover. In some cases the location of the sampling stations, selected prior to the planning of this project, was less than nominal when viewed through the "eyes" of the sensors.

F. TROPHIC INDICATORS AND A MULTIVARIATE TROPHIC INDEX

1. Trophic Indicators and Trophic State

Limnologists and other individuals concerned with lakes have used the term "trophic state" (i.e., degree of eutrophy) to describe two different lake characteristics, nutrient status and productivity. Thus, trophic state is a hybrid concept as suggested by Margalef (1958). A multiplicity of classificatory schemes has been devised to group and rank lakes. Examples of some approaches to lake typology are found in: Lueschow, et al. (1970), Rawson (1956, 1960), Margalef (1958), Hansen (1962), Jarnefelt (1958), Larking and Northcote (1958), Moyle (1945, 1946), Pennak (1958), Round (1958), Whipple (1898, Winner (1972), Zafar (1959), Beeton (1965), Donaldson (1969), and Gerd (1957). Hutchinson (1957, 1967) has reviewed many of the attempts to arrange lakes into orderly systems. Sheldon (1972) provides a particularly enlightening discussion on quantitative approaches to lake classification.

Perhaps no single area concerning eutrophication and trophic classification receives more attention than the selection of parameters used to characterize it. There are numerous indicators of trophic state, each with its merits and shortcomings. Reviews have been written on the subject by Fruh, et al. (1966), Stewart and Rohlich (1967), Vollenweider (1968), Taylor et al. (in preparation), and Hooper (1969). Wezernak and Polycyn (1972) have compiled a tabulation of indicators commonly used to assess eutrophication (Table 2-4). There is no universal agreement as to which (or how many) parameters adequately define the trophic state of a lake. The number and types of parameters used to reflect levels of eutrophication clearly indicate that no single parameter currently serves as a universal measure of trophic state. The use of a single indicator has the virtue of simplicity but may produce misleading rankings or groupings because lakes are normally too complex to be adequately gauged on such a simplified basis. On the other hand, the use of a large number of indicators may result in a problem of character redundancy.

Because of its multidimensional nature, lacustrine trophic state is amenable to analysis by multivariate statistical techniques. Multivariate techniques minimize the personal bias often present when data

Table 2-4. Trophic Indicators

Standard crop of algae and aquatic plants[a]
Amount of suspended solids[a]
Volume of algae[a]
Chlorophyll levels[a]
Number of algal blooms[a]
Transparency[a]
Plant regression[a]
Photosynthesis
Primary production
Aquatic plant nutrient content
Hypolimnetic oxygen concentrations
Sediment composition
Dissolved solids
Conductivity
Nutrient concentrations
Cation ratio (Na + K) / (Mg + Ca)

[a] Indicator may be remotely sensed using operational or near-operational sensors.

are examined for groups and rankings are developed. They are of particular value in situations where large numbers of objects or parameters are to be classified. Principal components analysis is one such technique meriting consideration as an approach to the problem of trophic index development.

2. Principal Components Ordination

Principal components analysis may be used to reduce the dimensionality of a multivariate system, such as water trophic indicators, by representing the original attributes as functions of the attributes (Boland 1976). This approach was also used by Shannon (1970) when he undertook the establishment of trophic state relationships for lakes in Florida. Wezernak, Tanis, and Bajza (1976) replicated this approach as well.

The objective of the principal components approach is to combine all of the various water quality measurements into a single numerical expression. In undertaking the principal components analysis approach it is required that the initial parameters selected (*i.e.*, the six trophic indicators) exhibit intercorrelations. The resulting index, the first principal component (PC1), thus represents the maximum total variation of any of the components.

The computation of principal components can be undertaken using either a covariance matrix (S) or a p x p matrix of Pearson product-moment correlation coefficients (r). Use of the r-matrix is indicated when the variates are measured in different units (*e.g.*, grams and meters). Computation of the r-matrix principal components involves the extraction of its eigenvalues (characteristic or latent roots) and eigenvectors (characteristic or latent vectors). The eigenvalues are a set of nonzero, positive scalar quantities. The sum of the r-matrix eigenvalues is the matrix trace and is equal to the number of dimensions in the original system (*i.e.*, the number of variates p). The rank of the matrix is equal to p.

Normalized eigenvectors give the A-space coordinates of an orthogonal set of axes known as the principal axes. The normalized eigenvectors are commonly designated as principal components.

The first principal component of the observations of the p-variates $X_1,\ldots,X_p$ is the linear compound

$$Y_1 = a_{11}\, X_1 + \ldots + a_{p1}\, X_p$$

whose coefficients (a_{11}) are the elements of the eigenvector associated with the largest eigenvalue of the r-matrix (Morrison 1967). The variance of the first principal component is associated with its eigenvalue. The jth principal component of the p-variate system is the linear compound

$$Y_j = a_{1j}\, X_1 + \ldots + a_{pj} X_p$$

whose coefficients are the elements of the eigenvector associated with the jth eigenvalue extracted from the r-matrix. The jth eigenvalue is a measure of the variance of the jth principal component.

The proportion of the total sample variance in the cloud of dimensionless standard scores attributable to any component is found by dividing its eigenvalue by p. The first principal component has the innate property of explaining the greatest proportion of the sample variance, and each successive component explains progressively smaller amounts of the toal sample variance. Frequently, as a consequence of the decreasing order of variance, $k < p$ dimensions will adequately summarize the variability of the original variates $X_1,\ldots,X_p$. The first three components generally account for most of the variation permitting the ordination of the subjects in 1-D, 2-D, and 3-D space. All of the dispersion in the data can be accounted for by using p dimensions, but this negates the analysis objective.

The principal components of N p-variate observations may be defined geometrically (Morrison 1967) as "...the new variates specified by the axes of a rigid rotation of the original response coordinate system into an orientation corresponding to the directions of maximum variance in the sample scatter configuration." The normalized eigenvectors give the directions of the new orthogonal axes and the eigenvalues determine the lengths (i.e., variance) of their respective axes. The coordinate system is expressed in standard units (zero means, unit variances) when the components are extracted from the r-matrix. Figure 2-16 is a hypothetical bivariate example of the geometric meaning of principal components. Principal components may be interpreted geometrically as the variates corresponding to the orthogonal principal axes of observation scatter in A-space. The elements of the first normalized eigenvector (i.e., coefficients of the first principal component) define the axis which passes through the direction of maximum variance in the scatter of observations. The associated eigenvalue corresponds to the length of the first principal axis and estimates the dispersion along it. The second principal component corresponds to the second principal axis, the length of which represents the maximum variance in that direction. In our example the first component accounts for most of the dispersion in the data swarm and the original 2-dimensional system could be summarized in one dimension with little loss of information. The new variate value (PC1) for each lake is obtained by evaluating the first component

$$Y_1 = aX_1 + bX_2$$

The PC1 for each lake in 1-D A-space is its coordinate on the first component axis and is shown diagrammatically by projecting each observation to the principal axis.

Detailed descriptions of the theoretical and computational aspects of principal components are found in Hotelling (1933a, 1933b, 1936), Anderson (1957), and Morrison (1967).

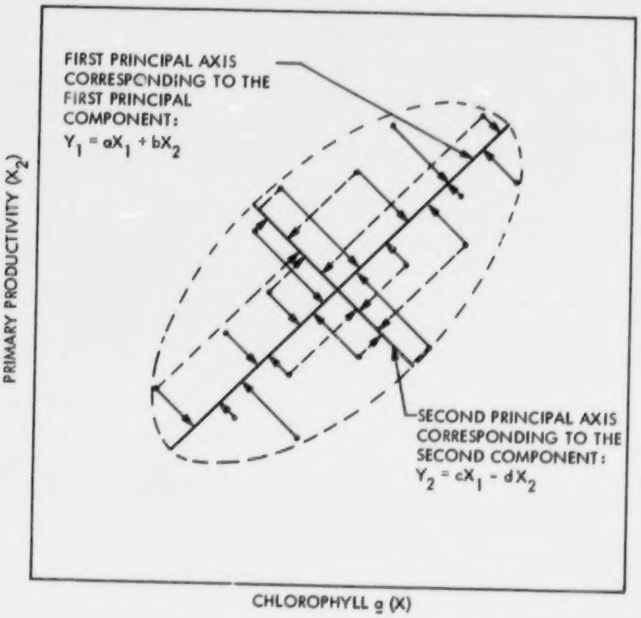
FIRST PRINCIPAL AXIS CORRESPONDING TO THE FIRST PRINCIPAL COMPONENT:
$Y_1 = aX_1 + bX_2$
PRIMARY PRODUCTIVITY (X_2)
SECOND PRINCIPAL AXIS CORRESPONDING TO THE SECOND COMPONENT:
$Y_2 = cX_1 - dX_2$
CHLOROPHYLL a (X)

Figure 2-16. Geometrical Interpretation of the Principal Components for a Hypothetical Bivariate System (modified from Brezonik and Shannon 1971)

G. MULTISPECTRAL CLASSIFICATION

The automated classification of remotely sensed water quality data is undertaken to determine whether trophic patterns, as determined by contact-sensed data, are discernible in multispectral data and to what extent these patterns can be mapped and correlated in different water bodies. Many algorithms exist which can be applied to multispectral data for purposes of classification. The one of interest in this study is the Bayesian maximum likelihood algorithm.

Like most spectral classification schemes, the Bayesian algorithm assumes gaussian distribution of its classes. Training area statistics are computed for each of the possible water quality types. These statistics, which consist of a mean multispectral signature and a covariance matrix, essentially instruct the classifier what it is to search for in spectral space.

Given these statistics, the classifier decides to which possible class a picture element belongs, based upon the probability of such an occurrence. All a priori probabilities are assumed equal. This procedure has the advantage of minimizing the probability of misclassification, hence the name "maximum likelihood."

Assume n multispectral channels of data. Mathematically, each picture element can be considered as an n-vector $X = (x_1, x_2 \ldots x_n)$, where x_j is the DN from channel J. For each training area ρ, compute the mean vector $X = (x_1\rho, x_2\rho \ldots x_n\rho)$ and the covariance matrix (n by n), $K\rho$ whose i, jth element is the covariance between channels i and j. The decision for class assignment is made by finding the class with the largest probability density function at the point X.

The probability density function for class is given by

$$P = \frac{1}{(2\pi)^{n/2}|K_\rho|^{1/2}} \exp\{-1/2(X - \bar{X}\rho)^T K^{-1} (X - \bar{X}\rho)\}$$

where $|K\rho| = \det(K\rho)$. In order to save computer time, it is not P that is computed, but rather $\log_e (P_\rho)$. This is appropriate since $\log_e$ is a monotonic increasing function and since one is only concerned with the P that gives rise to the largest P . Therefore one finds max $(Q\rho)$ where

$$Q\rho = \log_e(P_\rho) = C\rho - 1/2 \, (X - \bar{X} \,)^T K^{-1}(X - \bar{X}_\rho)$$

and

$$C\rho = -1/2(n \log_e[2\pi] + \log_e |K\rho|)$$

Each picture element is assigned to one of the possible classes in this manner.

The Bayesian maximum likelihood algorithm is considered to be an expensive classification algorithm in terms of computer time necessary. However, since only those picture elements which have been predetermined to be water are to be classified, and because of its sensitivity to subtle differences in spectral signatures, the Bayesian maximum likelihood algorithm continues to be used effectively in water quality classification studies.

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SECTION III

METHODS

A. DATA ACQUISITION

1. Contact-Sensed Water Quality Data

The water quality data were collected by helicopter-borne limnologists between August 22 and 25, 1975 inclusive (Table 3-1). The parameters measured and techniques employed are described in U.S. EPA (1975). With the exception of the algal assay yields, the data are reproduced in Appendix A. The parameters commanding attention in this investigation include chlorophyll a (CHLA), conductivity (COND), inverse of Secchi depth transparency (ISEC), total phosphorus (TPHOS), total organic nitrogen (TON), and algal assay yield (AAY).

2. Remotely Sensed Water Data

NASA-Houston provided an Orion P-3A aircraft equipped with a Bendix 11-channel modular multispectral scanner (MMS) and an aerial mapping camera outfitted with a 15.25-cm Zeiss lens and Kodak type SO397 film. The details of the August 25, 1975, flyover are found in Table 3-1 and Appendix B.

Table 3-1. Acquisition Dates for Colorado Lake Data

Lake/Reservoir Name	Date Water Sampled (1975)	Number of Sampling Stations	Data of Aircraft Flight (1975)	Landsat Overpass Date (1975)	Data Quality Remarks
Barker R.	Aug 26	2	Aug 25	Aug 23	Aircraft MMS sun glint
Barr L.	Aug 26	2	Aug 25	Aug 23	
Blue Mesa R.	Aug 25	6	Aug 25	Aug 24	Aircraft MMS sun glint
Cherry Creek R.	Aug 22	3	Aug 25	Aug 23	
Cucharas R.	Aug 22	1	Aug 25	Aug 22	Cloud cover; reservoir almost dry
Dillon R.	Aug 25	4	Aug 25	Aug 24	
Grand L.	Aug 26	2	Aug 25	Aug 24	
Green Mt. R.	Aug 25	3	Aug 25	Aug 24	Aircraft MMS sun glint

Table 3-1. Acquisition Dates for Colorado Lake Data (Continuation 1)

Lake/Reservoir Name	Date Water Sampled (1975)	Number of Sampling Stations	Data of Aircraft Flight (1975)	Landsat Overpass Date (1975)	Data Quality Remarks
Holbrook L.	Aug 22	1	Aug 25	Aug 22	Cloud cover on Landsat
Meredith R.	Aug 22	3	Aug 25	Aug 22	Cloud cover on Landsat
Milton R.	Aug 26	2	Aug 25	Aug 23	
Shadow Mt. R.	Aug 27	3	Aug 25	Aug 24	Aircraft MMS sun glint

Landsat-1 passed over the study area on August 22, 23, and 24. The Landsat-1 coverage of August 22 was not processed because of excessive cloud cover. Landsat-1 scenes of August 23 (5126-16474) and August 24 (5127-16532, 5127-16534) were selected for processing.

Of the 12 lakes under consideration, three (Cucharas, Holbrook, Meredith) were eliminated because of cloud cover on the Landsat scenes. Of the nine remaining lakes, four (Barker, Blue Mesa, Green Mountain, Shadow Mountain) were dropped from the MMS analyses because of sun glint. For multispectral analysis purposes, Landsat multispectral scanner (MSS) data were available for nine lakes and MMS data for five of the same nine lakes (see Table 3-2).

Each of the Landsat computer compatible tapes (CCT's) contained MSS data for all of the spectral bands (GRN, RED, IR1, IR2). Data acquisition with the MMS was less successful, with readable data being available for nine of the 11 channels. Only "noise" was found for Channels 5 and 6.

B. MULTISPECTRAL DATA PREPROCESSING

Prior to attempting classifications of any sort, certain corrections and processing are applied to both the Landsat and aircraft data. These preprocessing functions are applied not only to correct the imagery for cosmetic purposes but also for geometric reasons. The cosmetic processing relates to correcting for MSS line dropouts, slipped or missing lines, and other obvious defects in the MSS imagery. Similar types of corrections are also applied to the aircraft MMS data (Figure 3-1).

In terms of geometric corrections, the Landsat CCT's are not in a format compatible with the processing approaches used in the JPL Image Processing Laboratory (IPL). The CCT's, as received from the EROS data center, have the data from the four MSS bands interleaved. The IPL software program, VERTSLOG, unravels these interleaved data and creates a separate image for each band. The program also applies the various geometric corrections to the Landsat data. These corrections include scan mirror velocity, panorama correction and resampling the data to create an approximately 80-m IFOV (instantaneous field of view).

Landsat-1 MSS imagery is plagued by a striping problem, a consequence of an imbalance in sensors detectors. The MSS data were also preprocessed to reduce the magnitude of the striping problem, also known as "sixth line" banding.

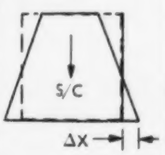
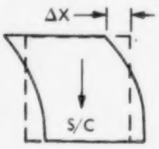
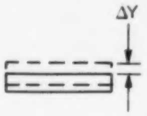
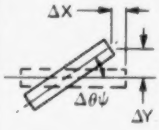
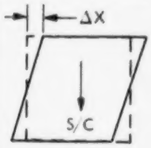
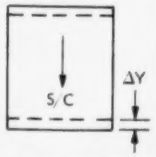
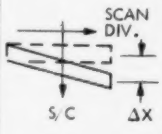
Similarly, the aircraft MMS data must be corrected so that the imagery has a 1:1 aspect ratio. The most obvious distortions seen in this imagery are square fields elongated into rectangles or circular irrigation patches which appear as ovals of high ellipticity. The cause of this appearance is related to a nonsynchronization of aircraft speed with the MMS scan mirror sweep rate. Figures 3-2 and 3-3 show circular fields before and after the aspect ratio has been adjusted.

Table 3-2. Availability of Remotely Sensed Data for 12 Colorado Lakes and 32 Lake Sampling Sites

Lake/Reservoir Name	Lake STORET Number	Sampling Site STORET Number	Zeiss	MSS	MMS
Barker R.	0801		x	x	
		080101	x	x	
		080102	x	x	
Barr L.	0802		x	x	x
		080201	x	x	x
		080202	x	x	x
Blue Mesa R.	0803		x	x	
		080301	x	x	
		080302	x	x	
		080303	x	x	
		080304	x	x	
		080305	x	x	
		080306	x	x	
Cherry Creek R.	0804		x	x	x
		080401	x	x	x
		080402	x	x	x
		080403	x	x	x

Table 3-2. Availability of Remotely Sensed Data for 12 Colorado Lakes and 32 Lake Sampling Sites (Continuation 1)

Lake/Reservoir Name	Lake STORET Number	Sampling Site STORET Number	Zeiss	MSS	MMS
Cucharas R.	0805		x		
		080501	x		
		080502	X		
Dillon R.	0806		x	x	x
		080601	x	x	x
		080602	x	x	x
		080603	x	x	x
		080604	x	x	x
Grand L.	0807		x	x	x
		080701	x	x	x
		080702	x	x	x
Green Mt. R.	0808		x	x	
		080801	x	x	
		080802	x	x	
		080803	x	x	
Holbrook L.	0809		x		
		080901	x		
Lake Meredith R.	0810		x		
		081001	x		
		081002	x		
		081003	x		
Milton R.	0811		x	x	x
		081101	x	x	x
		081102	x	x	x
Shadow Mt. R.	0813		x	x	
		081301	x	x	
		081302	x	x	
		081303	x	x	

PARAMETER	GEOMETRIC FOOTPRINT	MAGNITUDE OF CORRECTION - METERS ON THE GROUND
SCALE ADJUSTMENT - ALTITUDE VARIATIONS WITHIN A FRAME 9 CORRECTIONS WITHIN THE FRAME		$\Delta X = 9.26 \times 10^4 \frac{\Delta h}{h_n}$ (AT EDGE OF FRAME)
ATTITUDE VARIATIONS WITHIN A FRAME ROLL 9 CORRECTIONS WITHIN A FRAME		$\Delta X \approx h\Delta\theta_R$
PITCH 9 CORRECTIONS WITHIN A FRAME		$\Delta Y = h\Delta\theta_p$
YAW 9 CORRECTIONS WITHIN A FRAME		$\Delta X \approx 4.63 \times 10^4 (\Delta\theta\psi)^2$ $\Delta Y \approx 9.26 \times 10^4 \Delta\theta\psi$
IMAGE SKEW CAUSED BY EARTH ROTATION (FUNCTION OF LATITUDE)		$\Delta X \approx 8.88 \times 10^4\, a_{ER}$
AVERAGE VELOCITY CHANGE FROM NOMINAL		$\Delta Y \approx 8.88 \times 10^4 \frac{\Delta V}{V_n}$ (AT TOP AND BOTTOM OF FRAME)
IMAGE SKEW CAUSED BY FINITE SCAN TIME	 SCAN DIV. S/C ΔX	$\Delta X \approx 218$ METERS

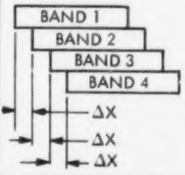
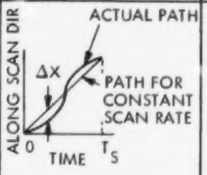
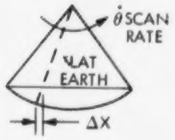
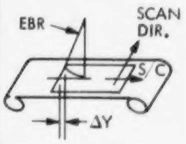
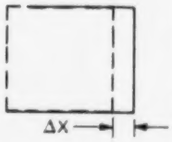
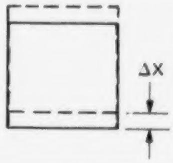
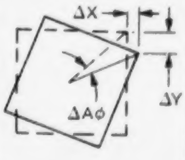
PARAMETER	GEOMETRIC FOOTPRINT	MAGNITUDE OF CORRECTION - METERS ON THE GROUND
SPECTRAL BAND OFFSETS	 BAND 1 BAND 2 BAND 3 BAND 4 ΔX ΔX ΔX	$\Delta X =$ 112 METERS
SCAN MIRROR VELOCITY CORRECTION	 ACTUAL PATH ALONG SCAN DIR ΔX PATH FOR CONSTANT SCAN RATE 0 TIME T_S	$\Delta X_{MAX} =$ 395 METERS
PERSPECTIVE CORRECTIONS SWEEP TO FRAME IN DIRECTION OF SCAN	 $\dot{\theta}$ SCAN RATE FLAT EARTH ΔX	$\Delta X_{MAX} =$ 115 METERS
FRAME CORRECTION IN DIRECTION OF SPACECRAFT TRAVEL - (EBR CORRECTION)	 EBR SCAN DIR. S/C ΔY	$\Delta Y_{MAX} =$ 64 METERS
ALIGNMENT CORRECTIONS - RELATIVE ALIGNMENT OF MSS TO AMS ROLL		$\Delta X = h\Delta A_R$
PITCH		$\Delta Y = h\Delta A_p$
YAW		$\Delta X \approx 8.88 \times 10^4 \Delta A\psi$ $\Delta Y \approx 9.26 \times 10^4 \Delta A\psi$

Figure 3-1. Geometric Corrections Typically Applied to Multispectral Scanner Data

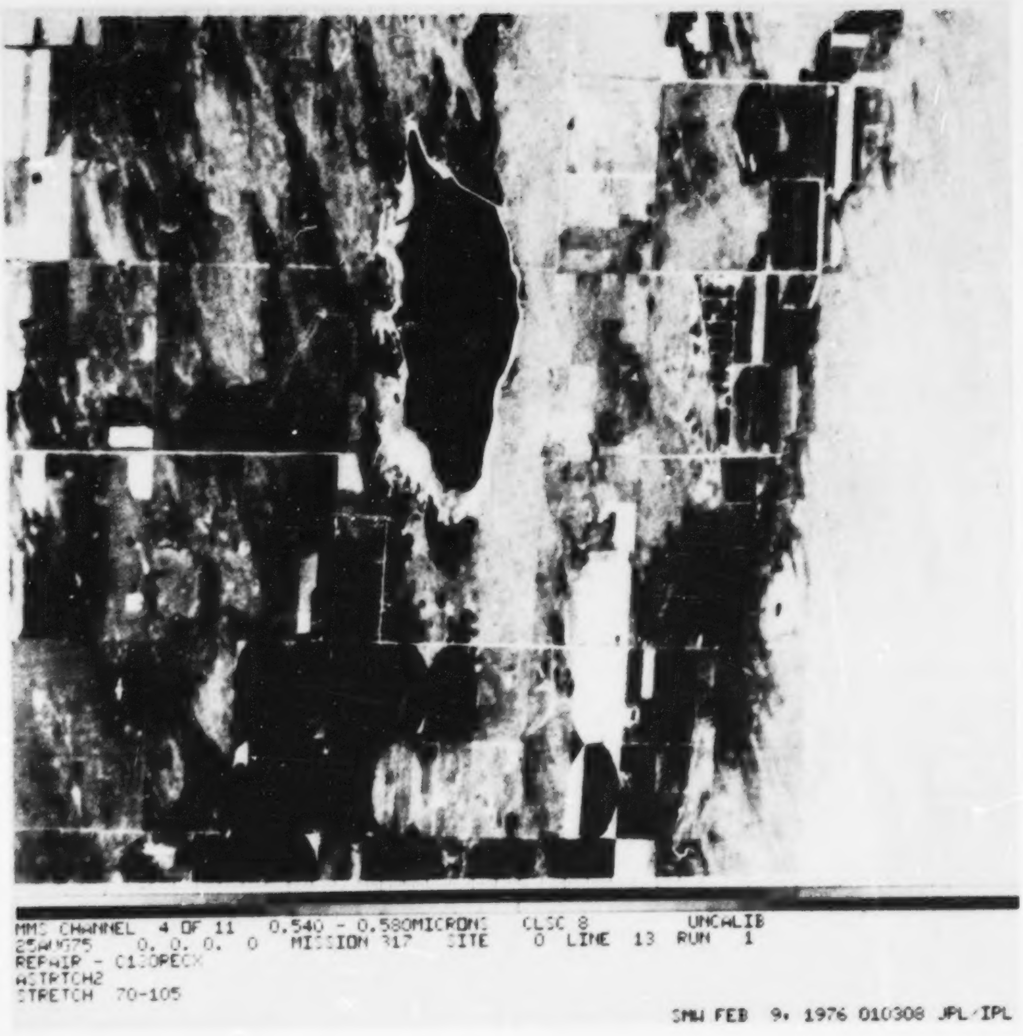

MMS CHANNEL 4 OF 11 0.540 - 0.580MICRONS CLSC 8 UNCALIB
25AUG75 0. 0. 0. 0 MISSION 317 SITE 0 LINE 13 RUN 1
REPAIR - C1COPECX
ASTRTCH2
STRETCH 70-105
SMW FEB 9, 1976 010308 JPL/IPL

Figure 3-2. Aircraft-Acquired MMS Imagery Before Geometric Corrections. The circular fields have been distorted into highly elliptical figures. The water body is Milton Reservoir. See Figure 3-3

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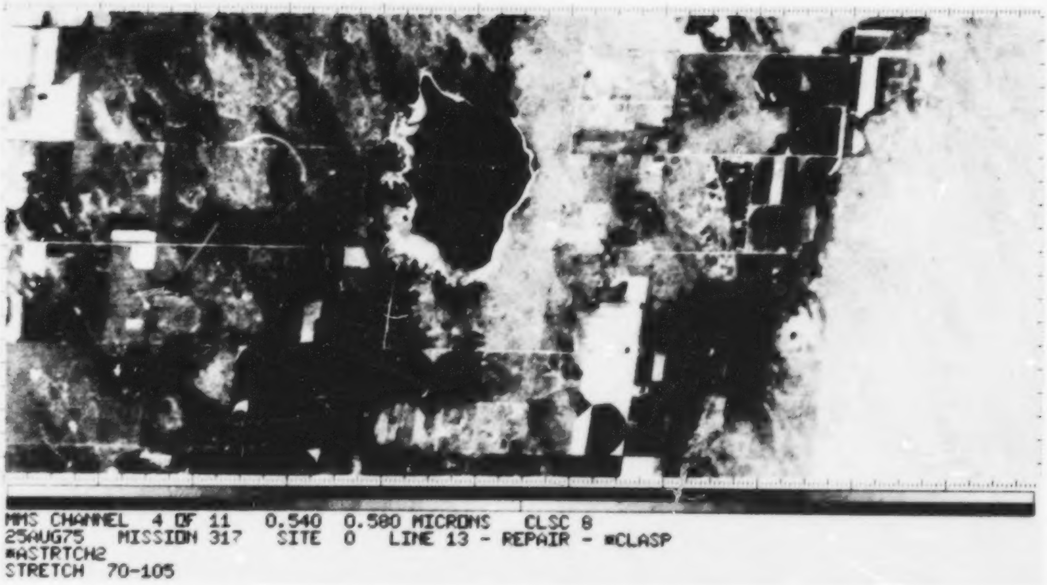
MMS CHANNEL 4 OF 11 0.540 0.580 MICRONS CLSC 8
25AUG75 MISSION 317 SITE 0 LINE 13 - REPAIR - *CLASP
*ASTRTCH2
STRETCH 70-105

Figure 3-3. Aircraft-Acquired MMS Imagery After Geometric Corrections Have Been Made

C. LAKE EXTRACTION METHODS

The primary thrust of this task is water quality monitoring and lake classification. At this time, the project is not concerned with land use or land use practices as they relate to water quality. The image processing techniques used were those designed to extract and manipulate MSS and MMS pixels representing surface water. The extraction procedure, explained in detail by Blackwell and Boland (1975), is outlined as follows using Landsat MSS for illustrative purposes. The approach uses the digital data contained on CCT's.

The MSS data for a Landsat scene are rescaled to 8 bits of precision using an IBM 360-65 and associated software and peripherals. The range of the new digital number (DN) scale is from 0 to 255 or a total of 256 DN levels for each of the four Landsat MSS bands. A hard copy image is then generated from the rescaled IR2 (Band 7) data. Using the newly generated photograph, a candidate lake is selected from the scene and a polygon is constructed around it. The polygon's coordinates are input to the computer system and four images are generated of the newly defined Landsat subscene, one for each of the four MSS bands. Each image, representing both water and surrounding terrain, and its histogram of DN values, is concatenated into a single photograph along with the three images representing the remaining bands (Figure 3-4).

Through inspection and after comparative testing it has been determined that the IR2 DN value of 28 provides optimum segregation of water and land features. A binary mask is developed from the IR2 extracted lake image. With this method, IR2 data values between 0 and 28 are set equal to 1 and all other IR2 DN values (29 to 255) are set equal to 0. The binary mask, in which water pixel values equal 1 and non-water pixel values equal 0, is then used to eliminate all but water-related features in the subscene. Multiplication of each MSS band subscene image (4 (GRN), 5 (RED), 6 (IR1), 7 (IR2)) pixel by its IR2 binary mask counterpart produces an image for each band. If processed correctly, the images will represent only pixels containing water-related information.

Figure 3-5 is a concatenation of the four subscene images after multiplication by the counterpart IR2 binary mask. Some final editing may be required to eliminate rivers, streams, and other water-related features not considered to be part of the lake proper. Once this has been accomplished, listings are generated of pixel counts, DN histograms, mean DN values for each band for the entire water body along with their associated standard deviations. At this point, the lake (or reservoir) is treated as a whole and mean DN values are for the overall water body.

Each of the nine lakes for which Landsat MSS data were available was processed in this manner. After final editing, the nine lakes were concatenated into a single image for further processing. Figure 3-6 is an example of the process output. The aircraft 11-channel MMS data were processed in a similar manner. Channel 10 data were used in the generation of the binary mask with a DN value of 60 being selected as the water cutoff point (*i.e.*, pixels with DN values of 60 or less were considered as representing water). Figure 3-7 is an IR2 concatenation of the five lakes for which MMS data were available.

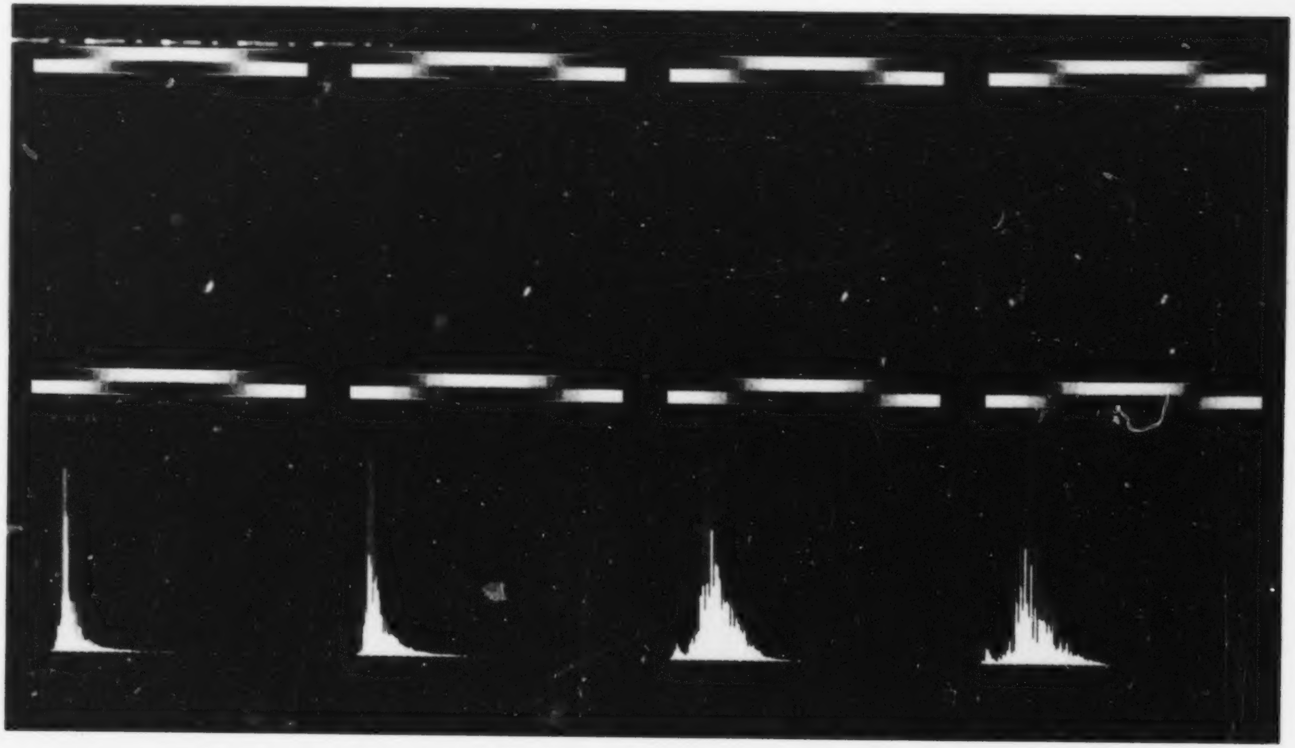

Figure 3-4. GRN, RED, IR1, and IR2 Images of a Landsat Scene 5127-16532 Subscene. The histograms depict the DN distributions for the subscene including both the water body and terrain. In the IR2 band, most of the water-related information is found in the DN range of 0-28. In most cases, IR2 DN values greater than 28 are related to terrestrial and atmospheric phenomena. The water body is Dillon Reservoir. Note the small cloud just southeast of the Blue River Arm. Its shadow is cast to the northwest, falling in part on the water, with most falling on the peninsula separating Frisco and Giberson Bays from the Blue River Arm

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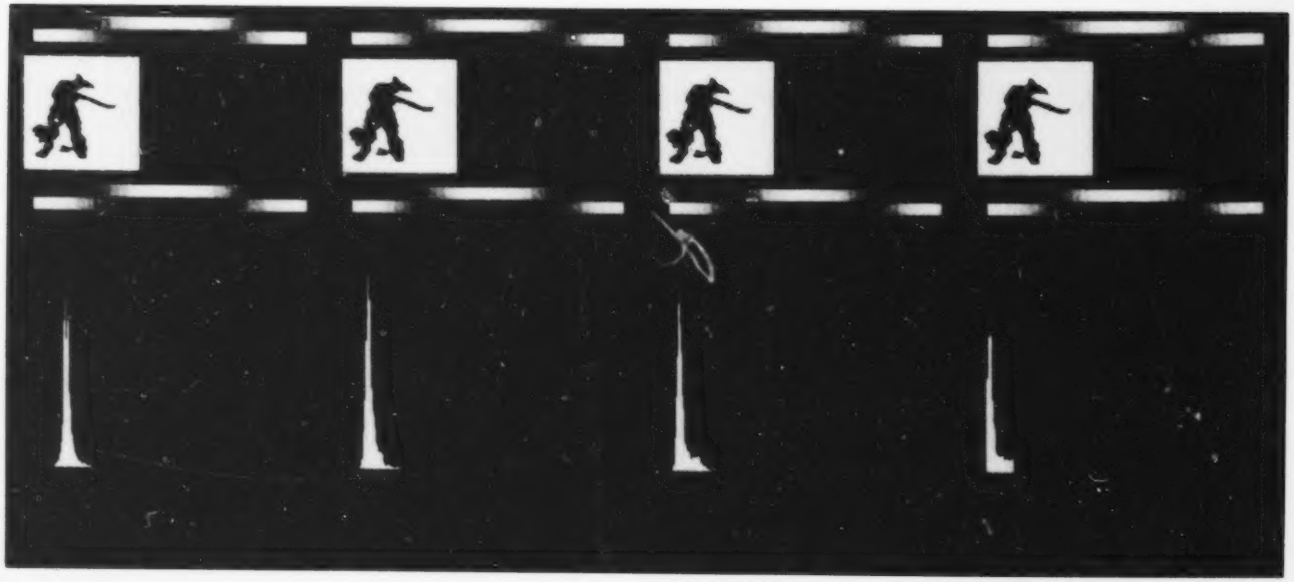

Figure 3-5. GRN, RED, IR1, and IR2 Images of a Landsat Scene 5127-16534 Subscene After the Application of the Binary Mask Generated Using the IR2 DN Range of 0-28 as Representing Water. See Figure 3-4. The histograms depict the DN distributions for the pixels comprising Dillon Reservoir. At this stage, the computer was unable to separate the shadow from the reservoir and it was necessary to manually override the computer, eliminating the cloud shadow through the use of an editing program

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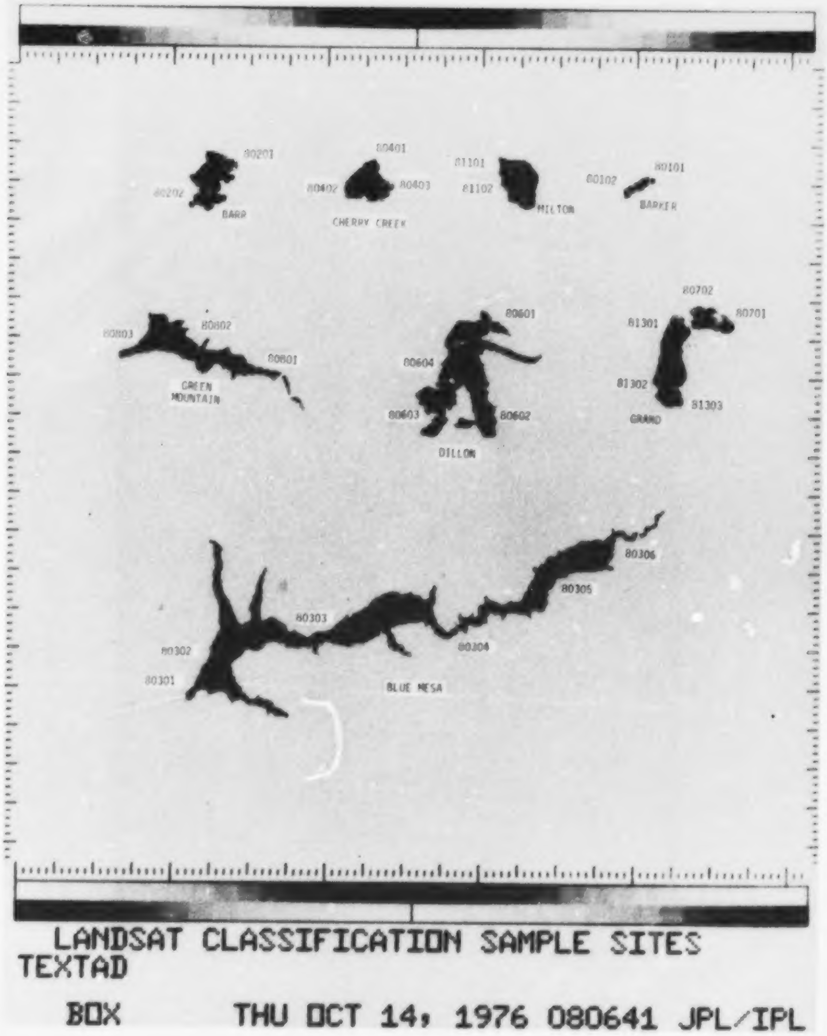
80201
80202
BARR
80401
80402
80403
CHERRY CREEK
81101
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MILTON
80102
80101
BARKER
80702
80701
81301
81302
81303
GRAND
80803
80802
80801
GREEN MOUNTAIN
80601
80604
80603
80602
DILLON
80306
80305
80303
80304
80302
80301
BLUE MESA
LANDSAT CLASSIFICATION SAMPLE SITES
TEXTAD
BOX THU OCT 14, 1976 080641 JPL/IPL

Figure 3-6. Landsat-1 MSS IR2 Concatenation of Nine Colorado Lakes. The boxlike figures define the MSS sampling sites and encompass the lake sampling stations

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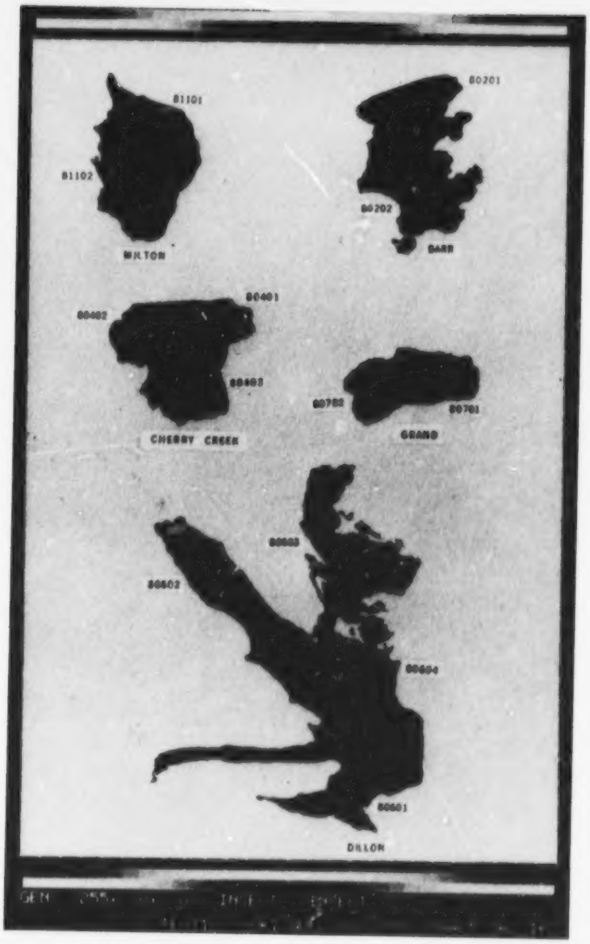
81101
81102
MILTON
80201
80202
BARR
80401
80402
80403
CHERRY CREEK
80702
80701
GRAND
80603
80602
80604
80601
DILLON

Figure 3-7. MMS Channel 10 Concatenation of Five Colorado Lakes. The boxlike figures define the MMS sampling sites and encompass the lake sampling stations

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D. WATER SAMPLE SITE LOCATIONS

Unlike remote-sensing problems related to land features, the problem of contact sampling site location and stability of the nature of the material or substance being sampled is an order of magnitude more difficult with water. Even when costly electronic positioning equipment such as Loran is used, there is a high degree of ambiguity inherent in ascertaining sampling site locations on large lakes. The field crews located the position of the helicopter (*i.e.*, the sampling site) by sighting on prominent land or cultural features with the helicopter compass and then estimating its distance from the shore and/or features. These locational data were recorded in the field notes and subsequently entered into the STORET data system along with the trophic indicator data.

Color photographic prints of the 12 lakes were made from the color transparencies supplied by NASA's Johnson Space Center. The aerial transparencies were taken from absolute altitudes ranging from 4600 to 6400 m using a Zeiss camera equipped with a 15.25-cm lens. Using the location data from STORET and sampling site locations marked on topographic maps by the field crew, each lake sampling site was pinpointed on the color prints by EPA personnel.

Since the Zeiss camera imagery also included sufficient cultural and landform features it was possible to establish visual ground control tie points in the extracted Landsat imagery as well as the aircraft 11-channel multispectral scanner imagery. With the aid of a Bendix datagrid coordinate digitizer it was possible to digitize the tie-point locations in the photographs as well as the sample site locations. With these data coordinates, a geometric transformation was made to map these locations onto the Landsat and aircraft multispectral scanner images. These locations are seen as the small rectangles within each lake in Figures 3-6 and 3-7.

Procedurely, the process consists of mapping a blank image containing tie-point locations and sample site positions on a lake to the same set of tie-points on the LANDSAT and aircraft imagery.

E. PIXEL DENSITY AT SAMPLE SITES

Once the sample site locations had been established for each lake, a decision was necessary relative to the matrix size of pixels to be used for the spectral analysis. In the previous task for the Wisconsin study (Boland 1976), all of the pixels for each lake had been used as the spectral training site. The selection of the appropriate matrix size for this application was guided in large part by the shape and size of some of the lakes. Some lakes, such as Blue Mesa, had very narrow sections which were only 4 to 6 pixels in width. With one or two exceptions the matrix size selected was 5-by-5, 4-by-4, or 3-by-3, depending on the lake and the sample location. The Landsat imagery being used was resampled to produce pixels measuring approximately 80 by 80 m. More specifically, the resampling produced square Landsat pixels representing an earth surface distance of 79.98 m per pixel edge. A resampled pixel represents an area of 6,396.8 m^2 (68,854.6 ft^2) or 0.6396 ha (1.58 acres). Therefore, the following pixel matrix sizes will represent

5-by-5 matrix = 15.99 ha = 39.54 acres
4-by-4 matrix = 10.23 ha = 25.30 acres
3-by-3 matrix = 5.76 ha = 14.23 acres

on the earth's surface. Figure 3-8 illustrates the areas these matrix sizes encompass relative to a standard U.S. one-mile-square section.

The aircraft modular multiband scanner (MMS) which was used to acquire intermediate altitude multispectral data of the same lakes produced, after geometry corrections, imagery with an average pixel resolution equal to 15 m. The pixel density or matrix size used to obtain MMS training site statistics was 11-by-11. This results in a ground area surface coverage of 2.72 ha (6.727 acres) per 11-by-11 MMS matrix sample site.

F. LAKE SURFACE AREA DETERMINATION

The surface area of many of the study lakes fluctuates greatly as a consequence of evaporation, and more importantly, drawdown, a result of irrigation and hydroelectric power demands. The use of area figures derived from reports and topographic sheets can only serve as "rough" reference values and are of little use in evaluating the area prediction capabilities of remote sensors in this study. Grand Lake and Shadow Mountain Reservoir are possible exceptions, because water level fluctuations are limited to 0.3 m by law.

An effort was therefore undertaken to determine the lakes' area using the well-accepted practice of taking the relevant measurements from vertical aerial photographs. The photos in this case were the 9-by-9 inch color prints supplied by JPL from the NASA overflight of August 25, 1975. The area of each lake was measured on its respective prints using a Numonics Model 253 electronic planimeter. The area of a lake's photographic image was measured four times, an average was computed, and then converted to hectares using the appropriate conversion factors. The results are displayed in Table 3-3. The computed values will serve as "target" figures for the Landsat MSS and MMS. Aerial photography was available for the 12 NES lakes and the calculations were made for each.

Landsat MSS-derived surface area estimates were made for 9 of the 12 lakes. The estimate for a specific lake was made by multiplying the sum of lake MSS pixels by the appropriate conversion factor. In other words,

$$\text{Area}_{(\text{ha})} = \Sigma \text{ pixels} \times 0.6396 \text{ ha/pixel}$$

MMS-derived surface area estimates were made for 5 of the 12 lakes. The estimate was made by multiplying the sum of the lake MMS pixels by the appropriate conversion factor.

$$\text{Area}_{(\text{ha})} = \Sigma \text{ pixels} \times 0.0225 \text{ ha/pixel}$$

An average pixel size of 225 m^2 was used for the MMS calculations.

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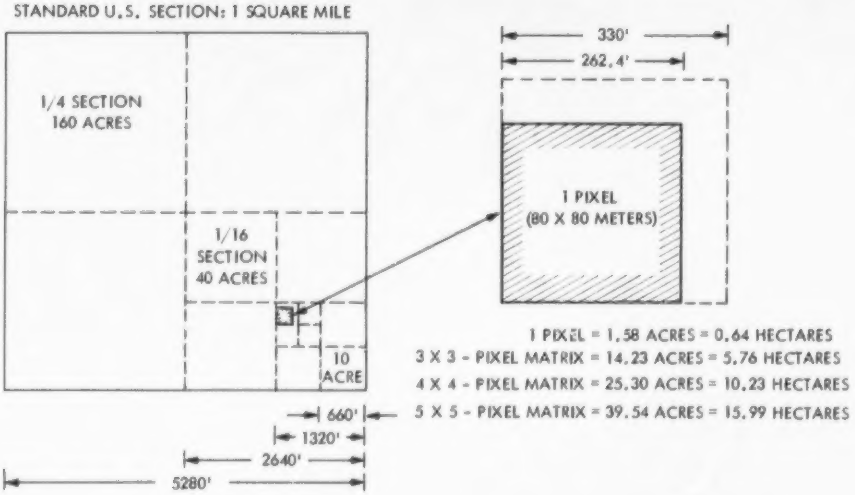
STANDARD U.S. SECTION: 1 SQUARE MILE
1/4 SECTION
160 ACRES
1/16
SECTION
40 ACRES
10
ACRE
660'
1320'
2640'
5280'
330'
262.4'
1 PIXEL
(80 X 80 METERS)
1 PIXEL = 1.58 ACRES = 0.64 HECTARES
3 X 3 - PIXEL MATRIX = 14.23 ACRES = 5.76 HECTARES
4 X 4 - PIXEL MATRIX = 25.30 ACRES = 10.23 HECTARES
5 X 5 - PIXEL MATRIX = 39.54 ACRES = 15.99 HECTARES

Figure 3-8. Landsat Pixel Size in Relation to the U.S. Standard One-Mile Section

Table 3-3. Area of Colorado Lakes As Determined From NASA Aerial Photographs

Lake/Reservoir Name	County	STORET Number	Pool Elevation, m	Absolute Aircraft Elevation,[a] m	Photograph Scale	Lake Area on Photograph, cm^2	Lake Surface Area, ha
Barker R.	Boulder	0801	2,495	5,670	1:37,200	5.87	81
Barr L.	Adams	0802	1,553	5,760	1:37,800	32.12	459
Blue Mesa R.	Gunnison	0803	2,292	5,740	1:37,667	217.62	3088[b]
Cherry Creek R.	Arapahoe	0804	1,691	5,640	1:37,000	25.74	352
Cucharas R.	Huerfano	0805	1,750	5,880	1:38,600	1.90	28
Dillon R.	Summit	0806	2,804	5,670	1:30,200	96.60	1337
Grand L.	Grand	0807	2,550	5,700	1:37,400	14.88	208
Green Mt. R.	Summit	0808	2,423	5,820	1:38,200	52.23	762
Holbrook L.	Otero	0809	1,269	6,400	1:42,000	4.86	86
Meredith R.	Crowley	0810	1,297	6,370	1:41,800	55.72	974
Milton R.	Weld	0811	1,463	5,850	1:38,400	26.22	386
Shadow Mt. R.	Grand	0813	2,550	5,670	1:37,200	36.94	511

[a] Based on aircraft radar altimeter.
[b] Several small areas of the lake fell outside the camera's field of view.

G. TROPHIC INDICATOR SELECTION AND MULTIVARIATE INDICES DEVELOPMENT

1. Tropic Indicator Selection

The NES, in the selection of water quality parameters, had to weigh parameter usefulness, length of acquisition time, and complexity of data reduction as well as other factors against resources, total number of lakes, and the element of time. Similarly, this particular feasibility study was constrained in the selection of trophic state indicators, with the following being selected for incorporation into a trophic state index (Table 3-4):

Table 3-4. Acronyms Used for Trophic Indicators

	Trophic Indicator	Units	Acronym
1.	Chlorophyll a	μg/l	CHLA
2.	Secchi disc transparency, inverse Secchi disc transparency	m, 1/m	SECCHI, ISEC
3.	Total phosphorus	mg/l	TPHOS
4.	Total organic nitrogen	mg/l	TON
5.	Conductivity	μmhos	COND
6.	Algal assay control yield[a]	mg/l [dry weight]	AAY

[a] Control samples of lakes water are spiked with various concentrations of phosphorus, nitrogen, and phosphorus plus nitrogen. Test cells of Selenastrum Capricornutum are injected into flasks with the controlled nutrients and allowed to incubate. The maximum growth attained is then quantified in terms of dry weight (mg/l).

In addition to being incorporated into a multivariate trophic index, each of the above parameters was used individually as the dependent parameter variable in attempts to develop regression models employing sensor bands or channels as independent variables. The trophic indicators had been used with some success in previous studies (e.g., Boland, 1976).

2. Multivariate Trophic Index Development

The indicators selected for principal components analysis are those previously listed: conductivity (COND, μmhos), chlorophyll a (CHLA, μg/l), algal assay yield (AAY, dry weight in mg) and Secchi disc transparency (Secchi, m). The inverse of Secchi disk transparency was employed (ISEC, m^{-1}) so that all indicator values would increase as the trophic state increases. Since the raw data seen in Table 3-5 are skewed, each trophic indicator value was natural log (LN) transformed to give a distribution more closely approximating a normal one. The transformed trophic indicator data are identified as follows: LNCHLA, LNISEC, LNCOND, LNTPHOS, LNTON, LNAAY. The data matrix was further standardized (zero mean, unit variance) by attributes using the relationship

$$z_{ij} = \frac{\overline{X}_{ij} - \overline{X}_i}{s_i}$$

where z_{ij} is the standardized values for attribute i of observation j (*i.e.*, lake), x_{ij} is the LN-transformed value of observation j, and $\bar{x}_i$ and s_i are the mean and standard deviation of attribute i, respectively. Eigenvectors and eigenvalues were then extracted from the associated correlation matrix. Next the first normalized eigenvector (principal component) was evaluated for each.

As described in some detail below, three multivariate trophic indices were developed for the Colorado lakes using the above approach. These indices are identified as PC1-11, PC1-13, and PC1-27. The PC1-11 was developed using "whole lake" parameter values; the others employed parameter values for a specific number of sampling sites (13 and 27), each treated as a separate observation or entity. While the original intention was to develop a "whole lake" index based on 12 lakes and a site index based on a total of 38 sampling sites, a combination of missing contacted-sensed and remotely sensed data resulted in the development of the three indices reported here.

a. *Eleven-Lake Index (PC1-11)*. The principal component-derived ranking of Colorado Lakes was accomplished using the mean trophic indicator values calculated from data collected for 11 lakes during August 22-26, 1975 (Table 3-5). As the data set for Lake Meredith was not complete at the time the analysis was run, it was excluded. The analysis was undertaken using the Statistical Interactive Programming System (SIPS) on a Control Data Corporation CDC 3300 digital computer at Oregon State University. The procedure used was that reported by Boland (1975, 1976) with one important exception. The original analysis, performed on 100 NES-sampled lakes, used trophic indicator values averaged over a sampling year consisting of three sampling rounds (spring, summer, fall); this time only the summer sampling round data were used. In both cases, the lakes were treated to generate a trophic scale on which each lake would have a number (*i.e.*, trophic index value (PC1)) defining its position.

b. *Twenty-Seven Site Index (PC1-27)*. In addition to treating each of the 11 lakes as an entity, the 27 sampling sites located on the 9 Colorado lakes for which Landsat coverage was available were also ordinated using principal components analysis. The same six trophic indicators were used but, with the exception of AAY, the data were averaged at each station where multidepth sampling occurred. The AAY values were determined from composite water samples, each representing all or several lake sampling sites. Therefore, the AAY values used for the 27 site principal components analysis were averages for whole lakes or, as in the case of Blue Mesa Reservoir, representative of two sets of of several sampling sites each.

Table 3-5. Trophic Indicator Values for 12 Colorado Lakes for August 1975 Sampling Period

Lake/Reservoir Name	STORET Number	CHLA, µg/1	ISEC, m^{-1}	SECCHI, m	TPHOS, mg/1	TON, mg/1	AAY, mg/1	COND, µmhos
Barker R.	0801xx[a]	3.7	0.461	2.17	0.015	0.180	0.5	30
	080101	3.7	0.410	2.44	0.016	0.180		29
	080102	3.7	0.525	1.91	0.014	0.180		32
Barr L.	0802xx	51.7	2.187	0.46	0.747	1.623	186.3	595
	080201	74.4	3.281	0.31	0.761	1.890		597
	080202	29.0	1.640	0.61	0.733	1.357		593
Blue Mesa R.	0803xx	4.9	0.490	2.04	0.022	0.277	0.7	152
	080301	6.0	0.547	1.83	0.059	0.380	0.4	123
	080302	4.1	0.787	1.27	0.020	0.180	0.4	132
	080303	4.6	0.437	2.29	0.019	0.180	0.4	160
	080304	4.2	0.410	2.44	0.022	0.197	0.9	167
	080305	5.2	0.394	2.54	0.025	0.143	0.9	180
	080306	5.4	0.525	1.905	0.020	0.150	0.9	180
Cherry Creek R.	0804xx	48.7	1.373	0.73	0.054	0.816	3.2	600
	080401	9.8	1.094	0.91	0.041	0.533		637
	080402	124.6	1.514	0.66	0.089	1.130		586
	080403	11.6	1.640	0.610	0.043	0.710		571
Cucharas R.	0805xx	27.4	3.937	0.25	0.263	1.48	1.9	849
	080501	27.4	3.937	0.25	0.263	1.48	1.9	849
Dillon R.	0806xx	2.3	0.120	8.33	0.009	0.190	0.3	92
	080601	2.2	0.219	4.57	0.008	0.200		89
	080602	2.5	0.193	5.18	0.009	0.180		93
	080603	2.1	0.066	15.24	0.011	0.180		91
	080604	2.4	0.156	6.40	0.006	0.158		89
Grand L.	0807xx	5.5	0.398	2.52	0.011	0.116	0.2	7
	080701	5.5	0.410	2.44	0.012	0.180		8
	080702	5.4	0.386	2.59	0.010	0.197		5
Green Mt. R.	0808xx	8.3	0.471	2.13	0.010	0.237	0.3	107
	080801	7.9	0.410	2.44	0.009	0.180		109
	080802	7.1	0.492	2.03	0.010	0.180		105
	080803	9.8	0.525	1.91	0.013	0.380		109
Holbrook L.	0809xx	146.9	5.624	0.17	0.367	2.96	63.3	2368
	080901	146.9	5.624	0.17	0.367	2.96		2368

Table 3-5. Trophic Indicator Values for 12 Colorado Lakes for August 1975 Sampling Period (Continuation 1)

Lake/Reservoir Name	STORET Number	CHLA, µg/1	ISEC, m^{-1}	SECCHI, m	TPHOS, mg/1	TON, mg/1	AAY, mg/1	COND, µmhos
Meredith R.	0810xx	146.9	3.698	0.27	0.357	4.21	40.2	7095
	081001	151.3	3.937	0.25	0.429	4.62		7096
	081002	151.3	3.579	0.28	0.406	4.52		7094
	081003	138.0	3.579	0.28	0.236	3.48		7095
Milton R.	0811xx	12.2	0.787	1.27	0.720	1.092	7.2	1295
	081101	8.3	0.656	1.52	0.714	1.050		1304
	081102	16.0	0.984	1.02	0.728	1.155		1282
Shadow Mt. R.	0813xx	6.2	0.562	1.78	0.025	0.320	0.5	24
	081301	8.1	0.656	1.52	0.049	0.330		24
	081302	6.5	0.525	1.91	0.021	0.347		25
	081303	3.9	0.525	1.91	0.018	0.330		24

[a] STORET numbers with xx, e.g., 0801xx, represent average values.

c. Thirteen-Site Index (PC1-13). MMS coverage was available for only 5 of the 12 study lakes. A trophic ranking was developed for the 13 sampling sites on the lakes (Barr, Cherry Creek, Grand, Dillon, and Milton) using the procedure described in the preceding paragraph.

H. ANALYSES OF TROPHIC INDICATOR, TROPHIC STATE INDEX, AND REMOTELY SENSED DATA RELATIONSHIPS

1. Introduction of Analysis Methods

As stated earlier, the specific objectives of the study include an evaluation of the Landsat MSS's capabilities, when used in conjunction with contact-sensed data, to (a) estimate lacustrine trophic state, (b) estimate several trophic state indicators including Secchi transparency and chlorophyll a, and (c) to aid in the development of lake thematic photomaps which depict trophic indicator magnitudes and trophic state as defined by a numeric index.

As the project was originally conceived, contact and remotely sensed data (aerial photography, MMS, MSS) would be obtained from 12 lakes including 33 sampling sites. Unfortunately, cloud cover and sun glint reduced the number of lakes and sampling stations available for analysis purposes (Table 3-2). In addition, the MMS did not produce usable data in channels 5 and 6.

Two basic approaches were employed to evaluate the feasibility of using Landsat MSS and Bendix MMS digital data in lake classification and monitoring programs:

(1) Correlation/regression approach.

(2) Baysian maximum likelihood-derived thematic mapping approach.

2. Correlation/Regression Method

Correlation and regression analysis is one approach used to determine the feasibility of using Landsat MSS and MMS data for the estimation of trophic indicator and trophic index magnitudes. Passive remote sensors, such as the Landsat MSS, are not capable of sensing all of the lake trophic indicators of interest to limnologists. For example, the MSS is not able to sense directly nutrients such as phosphorus and nitrogen. However, phosphorus and nitrogen can and often do stimulate the production of algae and macrophytes which can have a measurable effect on the water body's volume reflectance. Another trophic indicator, conductivity, also cannot be directly sensed by the multispectral scanners but may still correlate with the remotely sensed data because of secondary effects.

a. Dependent Variables. Correlation and regression analyses were made to determine statistical relationships between the remotely sensed data, both MMS and MSS, and the following contact-sensed parameters:

(1) Chlorophyll a (CHLA, LNCHLA).

(2) Inverse of Secchi depth (ISEC, LNISEC).

(3) Secchi depth (SEC, LNSEC).

(4) Total phosphorus (TPHOS, LNTPHOS).

(5) Total organic nitrogen (TON, LNTON).

(6) Algal assay yield (AAY, LNAAY).

(7) Conductivity (COND, LNCOND).

(8) Multivariate trophic state indices (PC1-11, PC1-13, PC1-27).

The above-listed trophic indicators and indices are treated as dependent variables and the MSS bands and MMS channels as independent variables.

b. Model Development and Adequacy Criteria. Most of the statistical analyses were made using the Oregon State University Statistical Interactive Programming System (SIPS) on a CDC 3300. The regression analyses were made using the backward selection procedure. Many different regression models were developed. Model selection was made using a combination of several guidelines:

(1) Multiple correlation coefficient: the larger the better.

(2) Mean residual square: the smaller the better.

(3) Individual regression coefficients: significant at 0.05 level of probability.

(4) Calculated F-value for regression: significant at 0.05 level of probability.

(5) Number of independent variables: avoid many because the number of observations is small.

The number of observations available for analysis purposes was relatively small (n = 9, 13, 27), thereby making model saturation an acute problem. For example, it is possible to obtain a large multiple correlation coefficient (R^2) simply by adding more independent variables to the regression model. In the case of Landsat MSS data the investigator has four basic values to work with (i.e., GRN, RED, IR1, IR2) in his regression analysis. However, the situation rapidly becomes complex when band ratios and other functions are used. Excluding the thermal channel, the MMS produced usable data in eight channels, and when the possible functions are considered, the picture becomes even more complex. With exception of some of the correlation analyses, the modeling effort on SIPS was limited to using the basic Landsat MSS and MMS values. Table 3-6 lists Landsat MSS functions considered and investigated by personnel at the Jet Propulsion Laboratory.

c. Analyses as Applied to Five Groups of Lakes and Sample Sites. The fragmentary character of the remotely sensed data, a consequence of cloud cover and sun glint, precluded the planned analyses of (a) 12 "whole" lakes and (b) 32 sampling sites. Instead, the modeling efforts were applied to the contact and remotely sensed data as segregated into five sets on the basis of remotely sensed data availablity. The analysis groups are

(1) Landsat MSS nine "whole" lake set.

(2) Landsat MSS 27-site set.

(3) Landsat MSS 13-site set.

(4) MMS 13-site set.

(5) Modified MMS 13-site set.

Each of the above approaches will be discussed below. The results of the correlation analyses and regression modeling efforts are reported in Section IV, Results and Discussion.

1) Landsat MSS Nine "Whole" Lake Set. This effort utilized Landsat MSS DN lake means for each of nine lakes along with their mean trophic indicator values. The trophic indicator means are found in Table 3-5 and the Landsat data are in Table 3-7. The trophic index values (PC1-11), generated through the principal components analysis of 11 Colorado lakes, are given in Table 4-4.

2) Landsat MSS 27-Site Set. Twenty-seven sampling sites were included in this modeling effort. The sites are located on the nine lakes for which Landsat MSS coverage was available. The trophic indication means are found in Table 3-5 and the Landsat data are in Table 3-8. The trophic index values (PC1-27) generated through the principal components analysis of water truth from the 27 sites, are given in Table 4-8.

3) Landsat MSS 13-Site Set. Although MSS data are available for the 27 sampling sites, MMS data are available for only 13 sites on a total of 5 lakes (Barr, Cherry Creek, Dillon, Grand, Milton). In an effort to compare Landsat MSS data with Bendix MMS data, correlation and regression analyses were performed using MSS data from the same 13 sites for which MMS data are available. The contact-sensed data used in the correlation and regression analyses are found in Table 3-5 and the Landsat MSS data in Table 3-8. The trophic state index (PC1-13) values, produced from a principal components analysis of the contact-sensed data for the 13 sites, are given in Table 4-11.

4) MMS 13-Site Set. MMS data are available for 5 of the 12 lakes (Barr, Cherry Creek, Dillon, Grand, Milton). With the exception of surface area determination, no "whole" lake analyses were conducted on the 5 lakes

using the MMS data in Table 3-9. The number of observations (N = 5) was considered to be too small to be of much value. Instead, an effort was made to analyze the MMS data for the 13 sites.

Correlation and regression analyses were run using the water truth in Table 3-5, the MMS channel values in Table 3-10, and the trophic index values in Table 4-11. The regression modeling was accomplished using two different approaches:

(1) Eight-channel approach: The modeling was initiated using eight of the nine available MMS channels as independent variables. The thermal channel was excluded. The full model was developed and then the backstep procedure was employed.

(2) Four-channel approach: Four MMS channels approximating the four Landsat MSS bands were selected for analysis. The MMS channels (4, 5, 8, 9) were then used as independent variables with the trophic indicators and trophic index serving as dependent variables.

5) Modified MMS 13-site Set. A correlation analysis of the MMS data for the 13 sampling sites indicated that, with exception of Channel 10, strong correlations exist between channels (Table 3-11). Mueller (1972) demonstrated the use of principal components analysis as a means of reducing the dimensionality of the data and at the same time generating new variables that are orthogonal. With this in mind the MMS data for the 13 sites were processed on SIPS using the multivariate subsystem principal components analysis program. The program outputs included the MMS-related variables: MMSPC1, ... MMSPC8. The data relating to the new variables are given in Table 4-16.

As in the "MSS 13-Site Set", two approaches were employed in the development of regression models for the prediction of trophic indicator and index magnitudes:

(1) Eight-variable approach: The modeling was initiated using the eight newly defined MMS variables (MMSPC1, ... , MMSPC8) as independent variables. The full regression model was developed and then the backstep procedure was employed.

(2) Four-variable approach: The first four principal component-derived MMS variables (MMSPC1, MMSPC2, MMSPC3, MMSPC4), representing 99.54% of the variation in the MMS data were then used as independent variables with the trophic indicators and trophic index serving as dependent variables.

The contact-sensed data and trophic index values used to develop regression models through the above two approaches are found in Tables 3-5 and 3-7, respectively.

Table 3-6. Landsat MSS Functions Investigated in Statistical Stepwise Regression Analysis. MSS data included means for 9 lakes and 27 sampling sites

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1. GRN
2. RED
3. IR1
4. IR2
5. GRN/RED
6. GRN/IR1
7. GRN/IR2
8. RED/IR1
9. RED/IR2
10. IR1/IR2
11. LN(GRN)
12. LN(RED)
13. LN(IR1)
14. LN(IR2)
15. GRN + RED/IR1 + IR2
16. GRN - RED/IR1 + IR2
17. RED - IR1/RED + IR1
18. IR1 - IR2/IR1 + IR2
19. LN(GRN)/AVG
20. LN(RED)/AVG
21. LN(IR1)/AVG
22. LN(IR2)/AVG
23. GRN - RED/IR1 + IR2 - RED - IR1/RED + IR1
24. RED - IR1/RED + IR1 - IR1 - IR2/IR1 + IR2
25. GRN - RED/IR1 + IR2 - IR1 - IR2/IR1 + IR2
26. LN(GRN)/AVG x LN(RED)/AVG
27. LN(GRN)/AVG x LN(IR1)/AVG
28. LN(GRN)/AVG x LN(IR2)/AVG
29. LN(RED)/AVG x LN(IR1)/AVG
30. LN(RED)/AVG x LN(IR2)/AVG
31. LN(IR1)/AVG x LN(IR2)/AVG
32. LN(GRN)/AVG x LN(RED)/AVG x LN(IR1)/AVG
33. LN(GRN)/AVG x LN(IR2)/AVG x LN(RED)/AVG
34. LN(GRN)/AVG x LN(IR2)/AVG x LN(IR1)/AVG
35. LN(RED)/AVG x LN(IR1)/AVG x LN(IR2)/AVG
36. (LN(RED)/AVG x LN(IR1)/AVG x LN(IR2)/AVG x LN(GRN)/AVG
37. GRN/SUM
38. RED/SUM
39. IR1/SUM
40. IR2/SUM

Table 3-7. Landsat MSS Mean Values and Standard Deviations for Nine Colorado Lakes (Destriped "Whole" Lake Data)

Lake/Reservoir Name	STORET Number	LANDSAT Date (1975)	Band Means and (Standard Deviations)				Number of Pixels
			GRN	RED	IR1	IR2	
Barker R.	0801	Aug 23	34.99 (2.38)	19.40 (3.88)	14.24 (6.01)	6.79 (6.45)	119
Barr L.	0802	Aug 23	46.99 (3.54)	29.32 (5.63)	22.41 (6.46)	7.58 (5.87)	647
Blue Mesa R.	0803	Aug 24	36.52 (3.93)	19.82 (5.42)	15.61 (14.99)	5.54 (5.66)	5,082
Cherry Creek R.	0804	Aug 23	46.59 (3.55)	29.58 (6.14)	16.02 (6.61)	6.09 (6.01)	517
Cucharas R.	0805		(Not available)				
Dillon R.	0806	Aug 24	34.01 (4.03)	19.02 (5.07)	14.34 (6.13)	7.26 (6.21)	2,114
Grand L.	0807	Aug 24	31.89 (2.47)	18.09 (3.12)	13.40 (7.04)	6.61 (6.62)	328
Green Mt. R.	0808	Aug 24	40.35 (3.34)	23.85 (4.19)	14.93 (5.65)	6.97 (5.78)	1,267
Holbrook L.	0809		(Not available)				
Lake Meredith R.	0810		(Not available)				
Milton R.	0811	Aug 23	42.03 (5.51)	23.47 (7.22)	14.41 (7.19)	5.04 (5.02)	584
Shadow Mt. R.	0813	Aug 24	33.87 (2.02)	19.50 (2.52)	13.50 (5.23)	5.96 (5.99)	862

Table 3-8. Landsat MSS Band Means for 27 Sampling Sites in 9 Colorado Lakes (Destriped Data)

Lake/Reservoir Name	Sampling Site	Landsat Band Means			
		GRN	RED	IR1	IR2
Barker R.	080101	33.44	17.89	11.78	2.89
	080102	34.81	19.25	12.31	4.31
Barr L.[a]	080201	44.40	24.56	21.12	6.08
	080202	48.36	31.16	17.16	4.00
Blue Mesa R.	080301	37.22	19.56	11.44	6.00
	080302	38.12	20.44	12.20	3.48
	080303	34.80	17.24	9.28	3.68
	080304	35.56	18.94	19.56	5.06
	080305	34.40	16.52	8.56	3.80
	080306	34.20	17.00	10.28	4.64
Cherry Creek R.[a]	080401	45.08	24.80	12.28	4.44
	080402	47.76	29.32	15.24	3.80
	080403	47.40	33.04	17.16	5.20
Dillon R.	080601	34.44	17.12	11.16	4.20
	080602	31.48	15.96	10.64	3.92
	080603	33.56	19.36	13.84	5.64
	080604	30.56	14.64	9.60	3.52
Grand L.[a]	080701	30.48	16.56	10.32	3.40
	080702	31.36	16.36	9.92	4.28
Green Mt. R.	080801	42.19	23.81	15.81	7.44
	080802	40.12	24.12	14.28	5.28
	080803	39.36	22.76	14.12	5.68
Milton R.[a]	081101	39.84	19.12	11.16	3.68
	081102	42.16	23.96	12.52	3.64
Shadow Mt. R.	081301	35.28	20.76	13.12	5.32
	081302	33.28	18.32	10.20	2.80
	081303	33.84	18.80	11.40	3.72

[a] Landsat MSS data for the 13 sampling sites associated with these 5 lakes were used in 13-site analyses.

Table 3-9. MMS Channel Means, Standard Deviations, and Pixel Counts for Five Colorado Lakes[a]

Lake/Reservoir Name	Lake STORET Number	MMS Channel Means and (Standard Deviations)											Number of Pixels
		1	2	3	4	5	6	7	8	9	10	11	
Dillon R.	0806	111.00 (5.00)	110.30 (6.87)	67.76 (5.70)	53.68 (5.01)	-	-	41.66 (3.81)	47.76 (4.21)	37.57 (4.71)	51.05 (4.59)	23.88 (7.58)	56,537
Grand L.	0807	115.40 (6.78)	105.50 (8.04)	70.62 (5.16)	56.30 (3.56)	-	-	44.51 (2.92)	51.17 (3.24)	41.84 (3.98)	54.80 (4.16)	44.50 (8.46)	9,773
Cherry Creek R.	0804	123.50 (6.02)	123.20 (8.47)	87.82 (6.39)	71.96 (5.09)	-	-	53.98 (4.79)	57.46 (5.34)	43.89 (5.90)	54.05 (5.42)	103.0 (9.44)	17,590
Barr L.	0802	124.0 (3.52)	115.90 (4.69)	81.43 (3.51)	71.08 (1.95)	-	-	50.01 (3.18)	62.65 (3.93)	48.69 (6.96)	52.80 (5.32)	106.6 7.78	19,247
Milton R.	0811	126.10 (5.36)	120.30 (7.02)	83.70 (5.35)	68.34 (4.67)	-	-	48.62 (4.53)	54.64 (6.27)	42.61 (6.66)	53.32 (4.36)	114.8 (9.27)	17,118

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[a] The channel mean for a lake was determined by summing the band DN values for all of the lake's pixels and then dividing by the total number of pixels.

Table 3-10. MMS Channel Means and Standard Deviations for 13 (11 x 11 Pixel Array) Sampling Sites in 5 Colorado Lakes

Lake/Reservoir Name	Sampling Site STORET Number	MMS Channel Means and (Standard Deviations)										
		1	2	3	4	5	6	7	8	9	10	11
Milton R.	081101	122.96[a] (2.37)[b]	118.49 (1.82)	82.88 (1.15)	67.79 (1.05)	-	-	46.89 (0.85)	52.31 (1.09)	40.81 (1.00)	52.50 (1.12)	121.26 (3.52)
Milton R.	081102	128.17 (3.18)	123.19 (1.64)	86.34 (1.07)	69.65 (0.99)	-	-	47.78 (0.78)	51.75 (0.76)	39.35 (0.81)	51.10 (1.03)	110.14 (2.44)
Barr L.	080201	122.75 (2.62)	112.68 (1.52)	78.98 (0.92)	69.83 (0.85)	-	-	47.82 (0.73)	59.84 (0.62)	45.73 (0.85)	52.25 (0.99)	109.01 (3.06)
Barr L.	080202	125.90 (2.67)	120.22 (1.44)	84.66 (0.96)	71.71 (0.72)	-	-	52.41 (0.83)	60.79 (0.77)	43.93 (0.75)	48.64 (0.58)	101.74 (3.94)
Cherry Creek R.	080402	131.84 (3.34)	133.53 (2.90)	95.07 (1.79)	77.08 (1.46)	-	-	56.98 (1.09)	60.34 (1.27)	47.20 (1.35)	58.09 (1.65)	94.50 (3.12)
Cherry Creek R.	080401	122.26 (3.82)	119.00 (1.96)	83.99 (1.27)	68.49 (1.21)	-	-	50.22 (1.01)	54.08 (1.24)	41.93 (1.31)	53.50 (1.01)	107.38 (3.91)
Cherry Creek R.	080403	122.74 (2.91)	122.20 (1.71)	87.63 (1.21)	72.16 (1.00)	-	-	54.40	56.45 (1.08)	40.26 (0.89)	49.26 (0.73)	102.26 (3.63)
Grand L.	080702	119.16 (3.88)	110.07 (2.95)	73.26 (2.03)	57.69 (1.46)	-	-	45.60 (1.24)	51.92 (1.30)	41.96 (1.58)	54.56 (1.23)	38.85 (2.70)
Grand L.	080701	117.22 (5.17)	108.97 (6.24)	72.96 (4.05)	57.71 (2.89)	-	-	45.57 (2.29)	52.07 (2.59)	42.25 (2.8)	54.67 (2.53)	44.17 (6.76)
Dillon R.	080603	111.75 (3.15)	99.04 (2.23)	66.00 (1.50)	52.07 (1.13)	-	-	40.90 (0.93)	47.30 (0.93)	36.84 (1.12)	50.80 (1.21)	22.62 (2.22)
Dillon R.	080604	108.18 (2.88)	94.75 (2.41)	63.00 (1.65)	49.54 (1.21)	-	-	38.60 (0.90)	44.12 (1.07)	33.56 (1.14)	47.04 (1.00)	19.92 (2.20)
Dillon R.	080602	113.76 (2.64)	106.69 (1.64)	72.46 (1.08)	56.60 (0.91)	-	-	44.11 (0.79)	50.05 (0.84)	39.88 (1.01)	53.16 (0.72)	24.38 (4.69)
Dillon R.	080601	113.03 (2.87)	103.70 (1.57)	71.88 (1.07)	57.70 (0.97)	-	-	41.41 (0.77)	46.68 (0.89)	35.29 (0.81)	48.04 (0.66)	22.22 (2.20)

[a] Average pixel value for (11 x 11) training site.
[b] ( ) - standard deviation.

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Table 3-11. Pearson Product-Moment Correlation Coefficients Generated From MMS Channels for 13 Sites Located in 5 Colorado Lakes[a]

MMS Channel	MMS Channel								
	1	2	3	4	7	8	9	10	11
1 (370-413 nm)	1.000	0.970	0.954	0.946	0.892	0.838	0.788	0.474	0.854
2 (440-490 nm)		1.000	0.992	0.952	0.941	0.801	0.743	0.489	0.824
3 (495-535 nm)			1.000	0.974	0.943	0.803	0.707	0.407	0.849
4 (540-580 nm)				1.000	0.929	0.877	0.748	0.322	0.904
7 (660-700 nm)					1.000	0.892	0.791	0.436	0.757
8 (700-740 nm)						1.000	0.920	0.406	0.747
9 (760-860 nm)							1.000	0.706	0.621
10 (970-1060 nm)								1.000	0.197
11 (8000-13000 nm)									1.000

[a] df = n-2 = 13 - 2 = 11 5% level = 0.553, 1% level = 0.684.

3. Bayesian Maximum Likelihood-Derived Thematic Mapping Method

Several standard procedures are followed in the development of color classification maps. The initial phase is the application of the Bayesian maximum likelihood algorithm to the multispectral data to achieve classification. Once a satisfactory classification has been achieved, a color image of the resulting thematic classification map is constructed to illustrate the trophic pattern identified and mapped by the Bayesian classifier.

a. Operational Aspects of Classification. The Bayesian maximum likelihood algorithm was chosen for use in this water quality classification effort because of its sensitivity to subtle differences in spectral signatures. Multispectral signatures of water quality classes typically have a great deal of overlap, especially in Landsat data. There is no easily determined dividing line between one class and another in terms of the multispectral data. Rather, there is a range of possible ambiguity unless the classification algorithm is very sensitive to data differences.

The operational aspects used to develop a number of spectral classes which are relatable to specific trophic indicators and multivariate trophic indices are as follows:

(1) Selection of training sites. The initial step is the selection of training sites which represent different phenomena of interest or a range of values for a particular parameter (*e.g.*, trophic indicator, multivariate trophic index). A training site may consist of just a few pixels or many thousands. It could, for example, consist of an entire lake or just a small portion of it. In this study, both whole lakes and specific portions of lakes were used as training sites. The training sites, consisting of subsections of the lakes, encompass the ground truth sampling sites (Figures 3-6 and 3-7). While it is recognized that the ground truth sites are geographic points and that an entire site falls into a single pixel, the Bayesian maximum likelihood algorithm operates on statistical parameters (means, covariance) to generate probability density functions. Thus, more than one pixel is required for each training area. Generally, 25 to 40 pixels are selected, although on occasions fewer are used. The use of more than one pixel dampens the noise produced by the sixth line banding. Ideally, a training site is homogeneous and the resulting spectral curves are unimodal.

(2) Analysis of training site statistics. After the selection of the training sites have been completed, descriptive statistics are generated for each site; the statistics describe each site in terms of its spectral properties as measured by the Landsat MSS and/or the Bendix MMS. If each site demonstrates a unique spectral signature and the classification site accuracies are acceptable, the next step is to proceed with the generation of the thematic mapping product. If the signature demonstrates a marked

overlapping or the classification site accuracies are too low, an effort is made to pool training sites (on the basis of spectral similarity) and/or select new sites. In this project, other than using the entire lake as a training site, site selection was limited to the NES sampling sites.

(3) Generation of the thematic photomaps. Once the decision has been made to extend the signatures to the entire water body or group of water bodies, the Bayesian maximum likelihood algorithm is applied to all of the data. This process is accomplished through a video information communication and retrieval application program which also outputs a classification map as an end product. The map is constructed as the program progresses through the classification of the water quality data. After a pixel has been assigned to a particular class, it is also assigned a corresponding DN in the output map which signifies the class to which it belongs. Thus a pixel assigned to class 4 is represented by DN=4, class 5 by DN=5, and so on. When the classification is completed on all the input data, a corresponding map delineating the trophic patterns as classified remains. This map is perhaps the single most important visual tool available to the water quality analyst to aid in the evaluation of the accuracy and significance of a classification.

b. Color Thematic Maps. As colors are more easily discerned than gray levels by the human eye, classification maps are normally reproduced in color for interpretation. Colors are created by mixtures of the three primary colors of blue, green and red. A color is chosen to correspond to each class represented, with special attention given to the ease with which these colors can be distinguished from one another. A wide range in colors is preferable, as colors from the same family closely resembling one another are easily confused when in close proximity. In lake classifications an attempt is also made to assign colors of blue and green to classes lying at the oligotrophic end of the relative trophic scale. This is done more for esthetic purposes and should not be construed as suggesting that classes represented by blues denote clear or pristine water. Once the desired colors have been selected, three separate positive images of the classification map are created. Each is individually contrast-enhanced in such a way as to produce a given hue when exposed through an individual primary filter. Each image is then registered to the other and is exposed separately through its corresponding filter of red, green, or blue. The result is a color image representing the classification map in as many different colors as there are classes.

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SECTION IV

RESULTS AND DISCUSSION

This section is devoted to the presentation of the analysis results and to discussions of pertinent aspects. The order of presentation is essentially the same as that used in Section III, Methods.

A. LAKE SURFACE AREA

The results of the lake surface area calculations as determined using data from three types of sensors (Zeiss camera, Landsat MSS, Bendix MMS) are given in Table 4-1. The estimates made from the Zeiss camera photographs are treated as the "ground truth." Although neither of the scanners was able to give an estimate that corresponded exactly with the Zeiss estimates, they did provide estimates that approximate the true values.

Three-sensor coverage was available for five of the lakes. Total surface area estimates for the five lakes are as follows:

Zeiss camera	2,742 ha
Landsat MSS	2,677 ha
Bendix MMS	2,706 ha

Landsat underestimated the total area of the five lakes by 2.37%. The Bendix MMS gave slightly better results, underestimating the area by 1.31 %.

Complete Landsat MSS and Bendix MMS coverage was available for eight of the nine lakes; Zeiss coverage for Blue Mesa was not complete. For the eight lakes, Landsat overshot the Zeiss estimates in four cases and underestimated in the remaining four cases. Total surface area estimates for the eight lakes are:

Zeiss	4096 ha
Landsat MSS	4114 ha

The Landsat MSS, on the basis of eight lakes, overestimated the total surface area by 0.40%.

Although the sample sizes are small (N = 5, N = 8), it is apparent that both Landsat and the Bendix MMS can provide estimates of lake surface area which are of practical value.

The approach used during this project to separate water pixels from pixels associated with other features including terrain and clouds is very simple. However, the approach, consisting of establishing an IR2 DN threshold value of 28 for Landsat (DN values from 0 to 28 as assumed to represent water) and a CH10 value of 60 for the MMS (DN values of 0-59 are assumed to represent water), can lead to problems. For example, if you examine the subscene of Landsat Scene 5127-16532

Table 4-1. Surface Area Estimates for Colorado Lakes Using Three Types of Sensors

Lake/Reservoir Name	STORET Number	Sensor Estimates		
		Zeiss Camera ha	Landsat MSS ha	Bendix MMS ha
Barker R.	0801	81	76	N/A[b]
Barr L.	0802	459	413	433
Blue Mesa R.	0803	3088[a]	3247	N/A
Cherry Creek R.	0804	352	330	396
Cucharas R.	0805	28	(clouds)	N/A
Dillon R.	0806	1337	1351	1272
Grand L.	0807	208	210	220
Green Mt. R.	0808	762	810	N/A
Holbrook, L.	0809	86	(clouds)	N/A
Lake Meredith R.	0810	974	(clouds)	N/A
Milton R.	0811	386	373	385
Shadow Mt. R.	0813	511	551	N/A

[a] Several small areas of the lake fell outside the camera's field of view.
[b] N/A = not available.

(Figure 3-4) you will note a small cloud just southeast of the Blue River Arm of Dillon Rerservoir. The cloud's shadow is cast to the northwest, falling in part on the water, with the remainder falling on the peninsula separating Frisco and Giberson Bays from the Blue River Arm. Using the Landsat 0 to 28 IR2 DN range as representing water, the computer was unable to separate the shadow from the water (*i.e.*, it included the cloud shadow as part of the water mass). Yet, if you further examine the cloud's shadow in the false-color image, you will note that it is not black like the water of the Blue Arm, but has a slightly bluish hue (the hue is very apparent on the image original). This suggests that the land portion of the cloud is separable if more than one spectral band is used in the water detection algorithm.

The pixels which straddle the water-land interface present another problem of substantial proportions when using a single-band water detection algorithm. These pixels, sometimes called "mixed" pixels, encompass both water and land and therefore provide a signal consisting of a mixture of spectral information. This can have an adverse impact on determination of the area of water bodies.

1. A Multiband Water Detection Algorithm

In this and past EPA/JPL Landsat lake classification efforts, the detection of pixels whose instantaneous field of view (IFOV) is that of water was done in the manner of thresholding the IR2 band. The low reflectance of water in this spectral range conveniently produced a bi-modal distribution of DNs: one peak for water, another peak for non-water. This technique works quite well except in cases where the IFOV of the scanner includes both water and non-water areas (e.g., the shoreline of a lake and cloud shadow on the water-land interface). In this situation, the problem becomes one of trying to estimate the proportion of each material in the IFOV.

Horowitz (1971) and Work and Gilmer (1976) have investigated the proportion estimation problem and have obtained encouraging results. Work and Gilmer estimated the proportions of water, bare soils, and green vegetation using Landsat bands 5 and 7. This technique requires an estimate of the spectral signature for pure water, pure bare soil, and pure vegetation. Although the spectral signature of water is fairly easy to estimate, that for soil and vegetation is more difficult. The many variables involved--*e.g.*, differences in type of soil, variations in type and thickness of vegetative cover--cause considerable error when estimation is attempted by a completely automatic processor.

An alternate approach meriting consideration treats the mixture classes as consisting of only water and non-water. Only bands 5 and 7 are used in the detection process, since it has been found that bands 4 and 6 offer little in additional information. The estimation of the spectral signature for water and non-water is made over a region within and immediately surrounding the water body.

The spectral signatures (mean DN values) were estimated by an iterative procedure. First the 2-dimensional space (band 5 vs band 7) is partitioned into two regions in which the populations of water and non-water typically cluster and the mean is then recomputed for those DNs which fall within the neighborhood of the initial mean. This process is continued until a convergent mean has been found for each region.

The proportion estimation implemented uses a technique proposed by McCloy (1977). In Figure 4-1 W is the mean for water, U is the mean for non-water, and P is the DN for any given pixel. P' is the projection of P onto the line segment WU. If /WU/ is the length of the line segment WU and /WP'/ is the length of line segment WP' then the proportion estimate q for water is

$$q = 1 - \frac{/WP'/}{/WU/}$$

where $0 \leq q \leq 1$.

If P' does not fall between W and U then it is given the position of the closest point, W or U. A decision threshold is set for q at which the pixel is defined to be water or non-water.

The necessary algorithm for the multiband approach described above was developed during the course of this project, but was not employed on Colorado lakes.

B. PRINCIPAL COMPONENT TROPHIC ORDINATION OF LAKES AND SAMPLING SITES INDICATORS

The principal components analysis of the six trophic indicators was undertaken to reduce the dimensionality of the data. The six natural logarithm-transformed indicators include LNCHLA, LNISEC, LNCOND, LNTPHOS, LNAAY, and LNTON. The analysis was performed once for each of three sets of data points. The results of each analysis will be discussed separately.

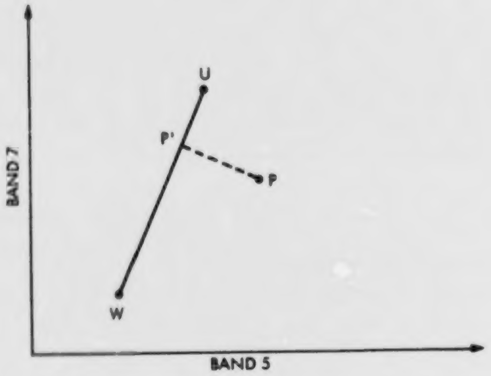

Figure 4-1. Proportion Estimation Diagram

1. Principal Component-Derived Trophic Ranking of Colorado Lakes

At the time the analysis was made, complete trophic indicator data sets were available for 11 of the 12 Colorado lakes (data for Lake Meredith were lacking). Although Landsat data were available for only nine lakes, the decision was made to generate the "whole" lake trophic ranking using as many contact-sensed Colorado lakes as possible.

The normalized eigenvectors and eigenvalues are found in Table 4-2. Although the principal components analysis is of value in reducing the dimensionality of a multivariate system, it is sometimes difficult to interpret the new variates in terms of subject matter identities. Some indication of a principal component's meaning may be ascertained by an examination of the algebraic sign and magnitude of its coefficients.

The coefficients of the first component (Table 4-2) are nearly equal in magnitude, suggesting that it represents a general measure of trophic state, accounting for approximately 86% of the variation in the data. Correlations between the new variate and the LN-transformed trophic indicators are found in Table 4-3. The first component correlates most strongly with LNTON ($r = 0.989$) and least with LNISEC ($r = 0.894$) (Table 4-3).

The second component (Table 4-2) explains about 6% of the variation in the trophic indicator data. It correlates best with LNCOND ($r = 0.367$) (Table 4-3).

The third component (Table 4-2) accounts for about 4% of the variation in the data. Together, the first three components explain about 97% of the variation in the trophic indicator data (Table 4-2).

The first component (Table 4-2) was evaluated for each of the lakes included in the analysis. This resulted in the generation of a numeric value for each of the lakes. The index (PC1-11) number defines the lake's position on a trophic scale. Table 4-4 displays the resulting PC1-11 values and rank position of the lakes. As the values increase, the trophic state increases. It is these values that were used in the nine "whole" lake correlation and regression analyses.

Although the details will not be presented in this report, once the Lake Meredith trophic indicator data set was complete, the principal components analysis was rerun using 12 lakes instead of the 11. The trophic index generated correlated strongly with that produced above ($r = 0.999$).

Again, it should be noted that the above principal components analysis used August sampling round data which is unlike that of Boland (1975), where the "whole" lake ranking was generated using annual means of the indicator data.

Table 4-2. Normalized Eigenvectors and Eigenvalues Extracted from 11 Colorado Lakes' Six Trophic Indicator Data Correlation Coefficient Matrix

Eigenvector Number	LNCHLA	LNCOND	LNISEC	LNTPHOS	LNTON	LNAAY	Eigenvalue	Variance, %	Cumulative Variance, %
1	0.409	0.392	0.400	0.408	0.434	0.405	5.187	86.45	86.45
2	-0.497	0.457	-0.599	0.379	0.073	0.191	0.374	6.23	92.68
3	-0.059	-0.687	-0.078	0.349	-0.151	0.612	0.245	4.08	96.77
4	-0.437	-0.189	0.435	0.570	0.111	-0.497	0.151	2.52	99.28
5	-0.614	0.156	0.490	-0.426	-0.005	0.420	0.028	0.47	99.75
6	-0.120	-0.325	-0.214	-0.248	-0.878	-0.046	0.015	0.25	100.00
							6.000		

Table 4-3. Product-Moment Correlation Coefficients for 6 Trophic Indicators and the Principal Components Extracted from the 11 Colorado Lakes' Data Correlation Coefficient Matrix[a]

Indicator	Principal Component					
	1	2	3	4	5	6
LNCHLA	0.931	-0.304	-0.029	-0.169	-0.103	-0.015
LNISEC	0.894	0.279	-0.340	-0.073	-0.026	-0.040
LNCOND	0.910	-0.367	-0.039	-0.169	-0.082	-0.026
LNTPHOS	0.928	0.232	0.173	0.221	-0.071	-0.031
LNTON	0.989	0.044	-0.075	0.043	-0.001	0.108
LNAAY	0.923	0.117	0.303	-0.193	0.070	-0.006

[a] At 9 degrees of freedom, the 0.05 level of significance is 0.602; the 0.01 level is 0.735.

The question arises, How well does the PC1-11 trophic ranking compare with those developed using other means? This question can be answered, in part, by comparing the resultant ranking with that developed by CERL for the same Colorado lakes. The CERL approach, described in detail in U.S. EPA (1974), employs a percentile ranking procedure. In this procedure, for each of the unweighted parameters used, the percentage of the Colorado lakes (N = 13) exceeding lake X in that parameter (e.g., chlorophyll a) was determined. The final ranking value or index number is simply the sum of the percentile ranks for each of the parameters used. The parameters incorporated into the CERL index include median total phosphorus, median inorganic nitrogen, mean chlorophyll a, median dissolved ortho-phosphorus, mean Secchi depth, and dissolved oxygen minimum. The values for mean Secchi depth and dissolved oxygen minimum are subtracted from the values of 500 and 15, respectively, so that all of the parameters contribute positively to the ranking. The means, medians, and minimum measures were calculated using data collected from all of the sampling rounds. A comparison of the two indices is shown in Table 4-5. When comparing the two indices,

Table 4-4. Trophic Ranking of 11 Colorado Lakes Derived From Principal Components Analysis of Six Trophic Indicators[a]

Lake/Reservoir Name	STORET Number	Rank	PC1-11 Value
Grand L.	0807	1	-2.59
Dillon R.	0806	2	-2.52
Barker R.	0801	3	-1.95
Green Mt. R.	0808	4	-1.49
Shadow Mt. R.	0813	5	-1.41
Blue Mesa R.	0803	6	-1.17
Cherry Creek R.	0804	7	1.11
Milton R.	0811	8	1.50
Cucharas R.	0805	9	1.89
Barr L.	0802	10	2.90
Holbrook L.	0809	11	3.74

[a] Cucharas Reservoir and Holbrook Reservoir trophic state index values were not used in Landsat MSS and Bendix MMS analyses because of cloud cover problems. The remaining 9 lakes' index values were used in the Landsat MSS 9-lake analyses.

Table 4-5. Rankings of 11 Colorado Lakes as Derived from Two Trophic Indices and Ordered by the PC1-11 Index

Lake/ Reservoir Name	PC1-11 Values	Rank	CERL Trophic Index Value	Rank	CERL Trophic Classification
Grand L.	-2.59	1	453	3	Mesotrophic
Dillon R.	-2.52	2	521	1	Oligotrophic
Barker R.	-1.95	3	358	5	Mesotrophic
Green R.	-1.49	4	479	2	Oligotrophic
Shadow Mountain R.	-1.41	5	433	4	Mesotrophic
Blue Mesa R.	-1.17	6	354	6	Mesotrophic
Cherry Creek R.	-1.11	7	291	7	Eutrophic
Milton R.	1.50	8	183	8.5	Eutrophic
Cucharas R.	1.89	9	157	9	Eutrophic
Barr	2.90	10	104	10	Eutrophic
Holbrook	3.74	11	183	8.5	Eutrophic

it should be kept in mind that they do not incorporate all of the same parameters and, in addition, the PC1-11 used only fall sampling round data. However, the agreement is very good between the two indices, the product-moment correlation coefficient (r) and rank correlation coefficients (Spearman's rho and Kendall's tau) being -0.922, -0.898, and -0.764, respectively. This close agreement does not provide direct evidence that the PC1-11 (and the CERL trophic index for that matter) adequately represents the trophic state of the water bodies. However, they do appear to be in general agreement with what has been observed in the field. Incidentally, the negative correlations are a consequence of the manner in which the two scales were constructed. In the case of the PC1-11 index, eutrophic lakes are located toward the positive end of the scale and oligotrophic lakes toward the negative end. Lakes with low rank sum values in the CERL index are considered to be eutrophic; those with high values are located toward the oligotrophic end of the scale.

2. Principal Component-Derived Trophic Ranking of 27 Sampling Sites on 9 Colorado Lakes

The preceding principal components analysis produced a trophic state index (PC1-11) which defines a lake's position on a numeric scale. The lake was treated as a whole unit. However, 27 contact-sensed data sites were established on the 9 lakes for which Landsat coverage is available. An analysis was conducted to rank each of the 27 sampling sites on a trophic scale. The normalized eigenvectors and eigenvalues are found in Table 4-6.

The coefficients of the first component (Table 4-6), with the exception of LNCOND, are of about the same magnitude and compare favorably with those of the first component derived from the 11-lake analysis (Table 4-2). About 78% of the data variation is explained by the first component (Table 4-6). With the exception of LNCOND, the first component exhibits high correlations with the trophic indicators (Table 4-7). The second component explains about 10% of the data variation (Table 4-6) and correlates best with LNCOND (Table 4-7). About 5% of the variation is explained by the third component, and correlations with the trophic indicators are less obvious. Together, the first three components are associated with approximately 93% of the variation.

The first component (Table 4-6) was evaluated for each of the 27 sampling sites included in the analysis. This resulted in a numeric value for each of the sites. The index (PC1-27) number defines a sampling site's position on a trophic scale. Table 4-8 lists the PC1-27 values and site rank. It is these values that were used in the Landsat 27-site trophic index analysis.

Table 4-6. Normalized Eigenvectors and Eigenvalues Extracted from 27 Colorado Lake Sampling Sites' 6 Trophic Indicator Data Correlation Coefficient Matrix[a]

Eigenvector Number	LNCHLA	LNISEC	LNCOND	LNTPHOS	LNTON	LNAAY	Eigenvalue	Variance, %	Cumulative Variance, %
1	0.405	0.396	0.347	0.428	0.437	0.430	4.702	78.37	78.37
2	-0.425	-0.484	0.735	0.165	-0.040	0.129	0.617	10.28	88.65
3	-0.375	-0.299	-0.576	0.524	0.243	0.328	0.303	5.05	93.37
4	-0.544	0.653	0.031	0.040	-0.437	0.290	0.188	3.13	96.83
5	0.327	-0.295	-0.086	-0.313	-0.390	0.741	0.121	2.02	98.85
6	-0.335	0.080	-0.003	-0.648	0.636	0.240	0.070	1.17	100.02
							6.001		

[a] The principal components analysis was performed using a r-matrix of correlation coefficients for six trophic state indictors. The natural log-transformed data were collected from 27 sampling stations in 9 Colorado lakes between August 22-26, 1975.

Table 4-7. Product-Moment Correlation Coefficients for 6 Trophic Indicators and the Principal Components Extracted from the 27 Colorado Lake Sampling Sites Data Correlation Coefficients Matrix[a]

Indicator	Principal Component					
	1	2	3	4	5	6
LNCHLA	0.877	-0.334	-0.207	-0.236	0.114	-0.088
LNISEC	0.858	-0.380	-0.165	0.283	-0.103	0.021
LNCOND	0.752	0.577	-0.317	0.014	-0.030	-0.001
LNTPHOS	0.927	0.130	0.286	0.017	-0.109	-0.171
LNTON	0.948	-0.032	0.134	-0.190	-0.136	0.168
LNAAY	0.933	0.101	0.181	0.126	0.258	0.064

[a] At 11 degrees of freedom, the 0.05 level of significance is 0.553; the 0.01 level is 0.684.

3. Principal Component-Derived Trophic Ranking of 13 Sampling Sites on 5 Colorado Lakes

MMS data were available for only 5 lakes containing 13 NES sampling sites. Because the 5 lakes are a very small sample, a trophic ranking was developed for the 13 sites. The resulting normalized eigenvectors and eigenvalues are found in Table 4-9.

With the exception of LNCOND, the coefficients of the first component are of the same general magnitude. The first component relates to about 83 % of the data variation (Table 4-9). It correlates strongly with all of the trophic indicators except LNCOND (Table 4-10). The second component explains about 10% of the variation and correlates most strongly with LNCOND (Table 4-10). Approximately 4% of the data variation is associated with the third component; correlations with the trophic indicators are low. The first three components explain about 96% of the variation.

The trophic index values (PC1-13) for the 13 sites are found in Table 4-11. The index values are used in the Landsat MSS and MMS trophic index analyses. Rather than generating the PC1-13 values for the 13 sites, the 13-site PC1 values could have been selected from the list of PC1-27 values (Table 4-8). A comparison was made of the PC1-13 and PC1-27 indices (Table 4-12). The product-moment correlation coefficient between the two indices is 0.9999. An arbitrary decision was made to use the PC1-13 values in MSS-MMS analyses of the 13 sites.

Table 4-8. Trophic Ranking of 27 Colorado Lake Sampling Sites Derived From Principal Components Analysis of 6 Trophic Indicators[a]

Rank	Lake/ Reservoir Name	Sampling Site STORET Number	PC1-27
1	Dillon R.	080603	-2.51
2	Dillon R.	080604	-2.28
3	Grand L.	080702	-2.01
4	Dillon R.	080602	-1.96
5	Dillon R.	080601	-1.93
6	Grand L.	080701	-1.85
7	Barker R.	080101	-1.41
8	Barker R.	080102	-1.30
9	Green Mt. R.	080801	-1.06
10	Green Mt. R.	080802	-0.99
11	Shadow Mt. R.	081303	-0.94
12	Blue Mesa R.	080303	-0.88
13	Blue Mesa R.	080305	-0.71
14	Blue Mesa R.	080302	-0.66
15	Blue Mesa R.	080304	-0.65
16	Shadow Mt. R.	081302	-0.64
17	Blue Mesa R.	080306	-0.59
18	Green Mt. R.	080803	-0.33
19	Shadow Mt. R.	081301	-0.23
20	Blue Mesa R.	080301	0.02
21	Cherry Creek. R	080401	1.54
22	Cherry Creek. R	080403	1.96
23	Milton R.	081101	2.78
24	Milton R.	081102	3.31
25	Cherry Creek R.	080402	3.39
26	Barr L.	080202	4.49
27	Barr L.	080201	5.43

[a] Indicators: LNCHLA, LNCOND, LNISEC, LNTPHOS, LNTON, LNAAY. The data incorporated into the analysis were collected August 22-26, 1975.

Table 4-9. Normalized Eigenvectors and Eigenvalues Extracted from 13 Colorado Lake Sampling Sites' 6 Trophic Indicator Data Product-Moment Correlation Matrix[a]

Eigenvector Number	LNCHLA	LNISEC	LNCOND	LNTPHOS	LNTON	LNAAY	Eigenvalue	Variance, %	Cumulative Variance, %
1	0.394	0.403	0.358	0.419	0.446	0.423	4.979	82.98	82.98
2	-0.511	-0.447	0.700	0.207	0.032	0.072	0.579	9.65	92.26
3	-0.339	-0.193	-0.578	0.541	-0.160	0.470	0.230	3.83	96.47
4	-0.581	0.670	0.072	-0.314	-0.140	0.300	0.122	2.03	98.50
5	-0.282	0.354	-0.064	0.504	-0.182	-0.710	0.086	1.43	99.93
6	-0.226	-0.162	-0.196	-0.370	-0.864	0.015	0.005	0.08	100.02
							6.001		

[a] The principal components analysis were performed using a r-matrix of correlation coefficients for six trophic state indicators (LNCHLA, LNISEC, LNCOND, LNTPHOS, LNTON, LNAAY). The natural log-transformed data were collected from 13 sampling stations in five Colorado lakes between August 22-26, 1975 by NES.

Table 4-10. Product-Moment Correlation Coefficients for 6 Trophic Indicators and the Principal Components Extracted from 13 Colorado Lake Sampling Sites Data Correlation Coefficient Matrix

Indicator	Principal Components					
	1	2	3	4	5	6
LNCHLA	0.880	-0.389	-0.163	- 203	-0.083	-0.015
LNISEC	0.900	-0.340	-0.093	-0.234	-0.104	-0.111
LNCOND	0.799	0.532	-0.277	0.025	-0.019	-0.014
LNTPHOS	0.935	0.157	0.260	-0.110	0.147	-0.025
LNTON	0.995	0.024	-0.008	-0.049	0.053	0.059
LNAAY	0.944	0.054	0.226	0.105	-0.208	-0.001

Table 4-11. Trophic State Index (PC1-13) Ranking Generated for 13 Colorado Lake Sampling Sites Using Principal Components Analysis of 6 Natural Log-Transformed Trophic Indicators[a]

Lake/ Reservoir Name	Sampling Site STORET Number	PC1-13	Rank
Barr L.	080201	3.47	13
	080202	2.78	12
Cherry Creek A.	080401	0.57	7
	080402	1.94	11
	080403	0.89	8
Dillon R.	080601	-2.05	6
	080602	-2.07	4
	080603	-2.46	1
	080604	-2.31	2
Grand L.	080701	-2.07	5
	080702	-2.18	3
Milton R.	081101	1.55	9
	081102	1.93	10

[a] Principal components analysis was performed using a r-matrix of correlation coefficients for six trophic indicators (LNCHLA, LNISEC, LNCOND, LNTPHOS, LNTON, LNAAY). The natural log-transformed data were collected from 13 sampling stations in 5 Colorado lakes between August 22 and 26, 1975.

Table 4-12. Comparison of Trophic State Index (PC1) Values for 13 Sampling Sites

Lake/ Reservoir Name	Sampling Site STORET Number	13-Site PC1 (PC1-13)	27-Site PC1 (PC1-27)
Barr L.	080201	3.47	5.43
	080202	2.78	4.49
Cherry Creek R.	080401	0.57	1.54
	080402	1.94	3.39
	080403	0.89	1.96
Dillon R.	080601	-2.05	-1.93
	080602	-2.07	-1.96
	080603	-2.46	-2.51
	080604	-2.31	-2.28
Grand L.	080701	-2.07	-1.85
	080702	-2.18	-2.01
Milton R.	0801101	1.55	2.78
	0801102	1.93	3.31
Range		5.93	7.94
Mean		0.00	0.80
Standard deviation		2.23	2.95
Correlation PC1-13, PC1-27		0.9999	

4. Some Aspects of the Multivariate Indices

The three multivariate trophic indices (PC1-11, PC1-27, and PC1-13) have much intuitive appeal. However, it should be kept in mind that they were developed from a relatively small number of sampling sites. While the assumption is made that the sites and the data collected at them are truly representative of the water bodies, this may not be the case. It may well be that more sites should have been sampled by the helicopter-borne field teams. It is not known what changes might have taken place in the rankings had the same number of sites been selected but at different locations in the water bodies.

As they now stand, the indices do not include any parameters directly relating to macrophyte distributions, much less macrophyte biomass. While such parameters would be desirable, they were not measured other than to note whether or not macrophytes were present.

The algal assay yield parameter included as one of the six trophic indicators in the indices development was measured in the laboratory under control conditions. Some credence must be given to criticisms suggesting that the inclusion of that parameter is inappropriate because of its laboratory derivation. The parameter was dropped from the principal components analysis scheme and three indices were developed using the remaining five trophic indicators: CHLA, COND, TPHOS, ISEC, and TPHOS. The correlations between the self-pairing members of the two sets (the three trophic indices derived from six indicators and the three indices derived from the five indicators) were highly significant (greater than 0.95), suggesting that little or no information was lost by dropping the algal assay yield parameter. The decision was made, however, to use the indices derived from the six indicators in the development of regression models and thematic classification products. The decision was arbitrary.

Up to this point, little attention has been given to the light inhibition effects that inorganic materials (e.g., silts, clays) can have on algae and submerged aquatic macrophytes. If available in substantial quantities, inorganic materials result in a reduction of the algal productivity of a lake through the reduction of light levels below those needed by the autotrophs to manufacture food. Thus, a water body may have very high nutrient levels but not experience algal blooms and/or major problems with macrophytes. As currently constructed, the index might result in some water bodies being incorrectly classified or ranked. It may be more fitting to segregate water bodies into two or more groups according to the primary contributor of turbidity (inorganic suspended sediments, volatile suspended sediments) and then constructing an index for each group.

The concept of a trophic index is usually thought of in terms of "whole" water bodies. In this project, trophic rankings were devised for both the lakes and reservoirs as whole bodies, and also for individual sampling sites. Each sampling site is treated as if it were an entity with its own unique values, which make it separable from the other members of the set. The CERL index, discussed in one of the preceding subsections, was not used on a sampling site basis, and therefore a parallel correlation analysis cannot be made. Once again, the principal component-derived indices do not account for the presence of aquatic macrophytes; this may result in some disparity between the indices and remotely sensed data because floating and emergent macrophytes can directly affect the character of the spectral curve(s).

C. CORRELATION AND REGRESSION ANALYSIS RESULTS

As indicated in the methods section, the fragmentary nature of the data set led to the organization of the data into five basic data sets for analysis purposes. The sets are:

(1) Landsat MSS nine "whole" lake set

(2) Landsat MSS 27-site set.

(3) Landsat MSS 13-site set.

(4) MMS 13-site set.

(5) Modified MMS 13-site set.

Correlations were calculated between each sensor's bands or channels, between the two sensors, and between the multispectral data and the trophic indicators and their associated multivariate trophic indices. Regression models for the estimation of trophic indicator and multivariate trophic indices' values were developed from each of the five sets of observations and, in the case of the modified MMS 13-site set, for two categories. It is recognized that some of the parameters estimated from the regression models are not directly sensible by the sensors and dependent on secondary effects.

Data sets (3), (4), and (5) are particularly interesting because they permit a direct comparison of the Landsat MSS and the MMS regression model results. Unfortunately, good MMS data were available from only five of the lakes, thus preventing comparisons both at the nine "whole" lake level and at the 27-site level.

In regression analysis, the term "independent variables" is often used to describe the parameters that will be used to predict another parameter, the dependent variable. As discussed by Draper and Smith (1966:4), the "independent" should not be interpreted too literally because two or more independent variables may vary together in some fashion. In general, this is not desirable because it, among other things, "...restricts the information on the separate roles of the variables--but it may be unavoidable" (Draper and Smith 1966: 4).

Table 4-13 displays the correlations between the Landsat MSS bands for three sets of observations. A very high correlation exists between the GRN and RED bands. This suggests a very limited amount of information is available to discriminate between their separate roles. The correlations decrease as the band separations increase; overall, IR2 correlates least with any of the bands. The MMS

Table 4-13. Landsat MSS Interband Product-Moment Correlation Coefficients for Three Sets of Observations

	GRN	RED	IR1	IR2
Set 1 (N = 9 "whole" lakes)				
GRN	1.000	0.981	0.727	0.022
RED		1.000	0.736	0.130
IR1			1.000	0.438
IR2				1.000
At 9-2 degrees of freedom, 0.05 level = 0.666, 0.01 level = 0.798				
Set 2 (N = 13 sites on 5 lakes)				
GRN	1.000	0.947	0.750	0.256
RED		1.000	0.768	0.300
IR1			1.000	0.694
IR2				1.000
At 13-2 degrees of freedom, 0.05 level = 0.553, 0.01 level = 0.684				
Set 3 (N = 27 sites on 9 lakes)				
GRN	1.000	0.943	0.660	0.320
RED		1.000	0.691	0.319
IR1			1.000	0.562
IR2				1.000
At 27-2 degrees of freedom, 0.05 level = 0.381, 0.01 level = 0.487				

interchannel correlation coefficients, based on data from 13 sites on five Colorado water bodies, are listed in Table 4-14. Again, it is noted that the correlations are highest between the shorter wavelength channels. A possible exception is CH11, the thermal channel. In general, as the distance between channels increases, the correlation coefficients decrease. This phenomenon is not unexpected. In addition, the bands and channels are relatively broad compared to those found in laboratory instrumentation designed for purposes of chemical analyses. Because of their spectral resolution, the sensors tend to average out the finer aspects of the spectral curves.

Present computer and software technology has made the development of regression models incorporating large data masses and many variables feasible; it is intuitively appealing to use "independent" variables that are not correlated. It is also desirable to avoid the use of variables that contribute little to the model(s). With this in mind, and as described in the methods section, a principal components analysis was made of the MMS channels CH1, CH2, CH3, CH4, CH7, CH8, CH9, and CH10; the thermal channel, CH11, was excluded from the analysis. The normalized eigenvectors and eigenvalues are displayed in Table 4-15. Unlike the principal components analysis used to develop the trophic indices, the covariance matrix for the MMS channels was used in place of the correlation matrix because all of the MMS data are measured in the same units. The new MMS variables and their associated data values are given in Table 4-16. The coefficients of correlation between the "old" variables and the "new" are in Table 4-17. The newly created channels (MMSPC1, ...,MMSPC8) are orthogonal or independent as demonstrated in Table 4-18; the correlation coefficients are essentially zero, though not exactly because of "rounding error."

The question arises, "How well do the Landsat bands correlate with the MMS channels?" Statistical relationships can be demonstrated using the scanner data collected from the 13 sites on five Colorado lakes (Table 4-19). Many of the correlations are statistically significant. For example, the (CH4, GRN) is 0.936, (CH7, RED) is 0.882 and (CH8, IR1) is 0.763. These values are especially high. Overall, the Landsat GRN band correlates best with the MMS channels; IR2 has the lowest correlations with the MMS channels. Based on the premise that the longer wavelengths are affected less by the atmosphere than the shorter wavelengths, it was expected that longer wavelength bands and channels would have larger correlation coefficients than, for example, the GRN and CH4. The unexpected correlations may be a consequence of weak signals received by the sensors (in particular Landsat) in the longer bands.

Table 4-20 presents the correlations between the Landsat bands and the "new" MMS channels developed through principal component analysis. The coefficients are large between the first "new" channel (MMSPC1) and Landsat GRN and RED. The principal component-derived variables contain a decreasing amount of information in the order MMSPC1, ..., MMSPC8. Ideally, most of the information would be contained in the first three or four variables.

Table 4-14. MMS Interchannel Product-Moment Correlation Coefficients Based on Data from 13 Sites

	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11
CH1	1.000	0.970	0.954	0.946	-	-	0.892	0.838	0.788	0.475	0.854
CH2		1.000	0.992	0.952	-	-	0.941	0.801	0.743	0.489	0.824
CH3			1.000	0.974	-	-	0.943	0.803	0.707	0.407	0.849
CH4				1.000	-	-	0.929	0.877	0.748	0.322	0.904
CH5					-	-	-	-	-	-	-
CH6						-	-	-	-	-	-
CH7							1.000	0.892	0.791	0.436	0.757
CH8								1.000	0.920	0.406	0.747
CH9									1.000	0.706	0.621
CH10										1.000	0.197
CH11											1.000

At 11 degrees of freedom. 0.05 level = 0.553, 0.01 level = 0.684

Table 4-15. Normalized Eigenvectors and Eigenvalues Extracted from 13 Colorado Lake Sampling Site, Eight-Channel MMS Data Covariance Matrix

Eigen-vector Number	CH1	CH2	CH3	CH4	CH7	CH8	CH9	CH10	Eigen-value	Variance, %	Cumulative Variance, %
1	0.347	0.551	0.474	0.442	0.264	0.237	0.158	0.073	378.613	92.235	92.235
2	0.026	-0.208	-0.305	-0.089	0.121	0.559	0.683	0.404	15.165	3.694	95.929
3	0.130	0.367	0.048	-0.455	-0.106	-0.436	0.060	0.666	10.904	2.656	98.585
4	-0.672	0.094	0.183	-0.188	0.675	0.033	-0.092	0.078	3.926	0.956	99.541
5	-0.460	-0.230	0.244	0.585	-0.351	-0.178	0.113	0.408	1.644	0.401	99.942
6	0.401	-0.437	-0.167	0.285	0.509	-0.208	-0.347	0.340	0.193	0.047	99.989
7	0.114	-0.339	0.601	-0.336	-0.189	0.441	-0.364	0.189	0.032	0.007	99.996
8	0.160	-0.388	0.444	-0.167	0.175	-0.412	0.577	-0.256	0.008	0.002	99.998
										99.998	99.998

Table 4-16. New MMS Variables and Associated Data Generated Through Principal Components Analysis of MMS Channels 1-4, 8-9 Data for 13 Sites in 5 Colorado Lakes

Lake Site STORET Number	MMS New Variable and Associated Data							
	MSSPC1	MSSPC2	MMSPC3	MMSPC4	MMSPC5	MMSPC6	MMSPC7	MMSPC8
081101	212.23	28.00	42.89	-35.34	-23.73	19.69	10.06	-3.98
081102	218.86	24.29	43.76	-37.51	-26.22	20.27	10.36	-3.84
080201	210.80	37.41	36.38	-36.43	-23.27	20.49	10.28	-3.86
080202	220.46	32.56	35.58	-34.14	-27.42	19.58	10.39	-3.78
080402	239.47	32.38	45.54	-32.48	-24.84	20.44	10.53	-3.81
080403	214.65	29.95	42.33	-32.47	-23.80	20.48	10.17	-3.67
080401	221.02	26.97	37.71	-29.79	-25.53	20.48	10.15	-3.95
080702	197.15	34.64	45.09	-34.26	-26.81	20.30	10.13	-3.84
080701	195.82	35.21	44.43	-33.15	-25.66	19.95	10.09	-3.79
080603	179.16	31.69	41.93	-33.74	-25.55	20.83	10.56	-3.95
080604	170.86	28.08	39.81	-33.47	-25.66	20.40	10.18	-3.79
080602	191.29	32.49	43.51	-31.88	-24.33	19.31	10.50	-3.90
080601	186.98	26.13	39.87	-33.90	-23.86	19.91	10.45	-3.72

Table 4-17. Pearson Product-Moment Correlation Coefficients of Eight Channel MMS Data for 13 Colorado Lake Sampling Sites and Associated Principal Components

MMS Channel	Principal Components							
	MMSPC1	MMSPC2	MMSPC3	MMSPC4	MMSPC5	MMSPC6	MMSPC7	MMSPC8
1	0.975	0.015	0.062	-0.192	-0.085	0.025	0.003	0.002
2	0.990	-0.075	0.112	0.017	-0.027	-0.018	-0.006	-0.003
3	0.990	-0.128	0.017	0.039	0.034	-0.008	0.012	0.004
4	0.980	-0.039	-0.168	-0.043	0.086	0.014	-0.007	-0.002
5	-	-	-	-	-	-	-	-
6	-	-	-	-	-	-	-	-
7	0.958	0.087	-0.065	0.249	-0.084	0.042	-0.006	0.003
8	0.869	0.410	-0.271	0.013	-0.043	-0.017	0.015	-0.007
9	0.791	0.605	0.051	-0.047	0.037	-0.039	-0.017	0.014
10	0.457	0.506	0.708	0.050	0.168	0.048	0.011	-0.008

Table 4-18. Product-Moment Correlation Coefficients Between "New" MMS Channels Developed from Principal Component Analysis of MMS Data from 13 Sites

"New" Channels			Correlation Coefficient
MMSPC1	,MMSPC2	=	1.950902922E-008
MMSPC1	,MMSPC3	=	1.017656610E-010
MMSPC1	,MMSPC4	=	-4.364543434E-008
MMSPC1	,MMSPC5	=	-8.158675052E-010
MMSPC1	,MMSPC6	=	4.664763204E-007
MMSPC1	,MMSPC7	=	-1.155939702E-009
MMSPC1	,MMSPC8	=	6.475880184E-007
MMSPC2	,MMSPC3	=	6.865259266E-011
MMSPC2	,MMSPC4	=	-2.176259774E-009
MMSPC2	,MMSPC5	=	1.954145026E-008
MMSPC2	,MMSPC6	=	-2.930489124E-008
MMSPC2	,MMSPC7	=	2.241735482E-007
MMSPC2	,MMSPC8	=	-1.215319346E-006
MMSPC3	,MMSPC4	=	4.225637112E-011
MMSPC3	,MMSPC5	=	-3.832076098E-006
MMSPC3	,MMSPC6	=	9.697340292E-008
MMSPC3	,MMSPC7	=	0.000031555
MMSPC3	,MMSPC8	=	4.486070722E-006
MMSPC4	,MMSPC5	=	-1.090250368E-009
MMSPC4	,MMSPC6	=	-3.570639032E-010
MMSPC4	,MMSPC7	=	9.135440976E-009
MMSPC4	,MMSPC8	=	-9.139718356E-007
MMSPC5	,MMSPC6	=	9.125326640E-007
MMSPC5	,MMSPC7	=	-3.150138508E-006
MMSPC5	,MMSPC8	=	6.604071588E-010
MMSPC6	,MMSPC7	=	-0.000019889
MMSPC6	,MMSPC8	=	6.998971632E-007
MMSPC7	,MMSPC8	=	1.035251884E-007

Table 4-19. Pearson Product-Moment Correlation Coefficients Between Landsat MSS Bands and MMS Channels for 13 Sampling Sites on 5 Colorado Lakes[a,b]

MMS Channel		Landsat MSS Band GRN [500-600 nm]	 RED [600-700 nm]	 IR1 [700-800 nm]	 IR2 [800-1,100 nm]
CH1	[370-413 nm]	0.824	0.756	0.498	-0.050
CH2	[440-490 nm]	0.827	0.777	0.426	-0.105
CH3	[495-535 nm]	0.877	0.821	0.483	-0.051
CH4	[540-580 nm]	0.936	0.863	0.639	0.089
CH5		(MMS data missing)			
CH6		(MMS data missing)			
CH7	[660-700 nm]	0.864	0.882	0.568	0.053
CH8	[700-740 nm]	0.825	0.812	0.763	0.234
CH9	[760-860 nm]	0.606	0.563	0.561	0.131
CH10	[970-1060 nm]	0.083	0.035	-0.041	-0.122
CH11	[8000-13000 nm]	0.865	0.735	0.568	0.108

[a] The lakes are Barr, Cherry Creek, Grand, Dillon and Milton.
[b] 5% level = 0.553, 11 d.f. 1% level = 0.684, 11 d.f.

Table 4-20. Pearson Product-Moment Correlation Coefficients Between Landsat MSS Bands and MMS Principal Component-Derived Variables for 13 Sampling Sites on 5 Colorado Lakes

MMS Variable	Landsat MSS Band			
	GRN	RED	IR1	IR2
MMSPC1	0.877	0.825	0.537	-0.010
MMSPC2	-0.102	-0.069	0.297	0.305
MMSPC3	-0.401	-0.427	-0.660	-0.492
MMSPC4	0.022	0.204	-0.066	0.024
MMSPC5	0.053	-0.152	0.099	0.267
MMSPC6	0.153	0.201	0.276	0.544
MMSPC7	0.081	0.127	0.220	0.188
MMSPC8	0.037	-0.035	-0.187	-0.312

Up to this point, only correlations between the remotely-sensed spectral data and transformed spectral data have been examined. Of particular interest to the limnologist are the correlations between the contact-sensed data and the multispectral data (i.e., the correlations between the ground or water truth and the multispectral data). The correlations for the five sets of observations (i.e., the five data sets discussed previously in this section) are displayed in Tables 4-21 to 4-25, inclusive. Overall, the correlations decline as the set size increases. In general, the aircraft-borne MMS channels correlate better with the contact-sensed data than the Landsat bands.

Correlations do not demonstrate cause and effect relationships. As mentioned earlier, not all of the trophic indicators can be sensed directly by the remote sensors. Such indicators include conductivity, total phosphorus, and algal assay yield. However, statistically significant correlations may exist between the remotely acquired data and "nonsensible" indicators, a consequence of secondary effects. If correlations of a relatively large magnitude exist, predictive models can be developed.

Table 4-21. Pearson Product-Moment Correlation Coefficients for 9 Colorado Lakes (August 1975 Contact-Sensed and Destriped MSS Data)

MSS Bands	PC1	CHLA (LNCHLA)	COND (LNCOND)	SEC (LNSEC)	ISEC (LNISEC)	TPHOS (LNTPHOS)	TON (LNTON)	AAY (LNAAY)
GRN	0.910	0.881 (0.916)	0.688 (-0.861)	0.545 (-0.807)	0.849 (0.807)	0.625 (0.723)	0.845 (0.888)	0.578 (0.816)
RED	0.865	0.938 (0.950)	0.582 (0.764)	-0.534 (-0.814)	0.877 (0.814)	0.539 (0.646)	0.810 (0.840)	0.597 (0.783)
IR1	0.761	0.799 (0.707)	0.327 (0.539)	-0.351 (-0.684)	0.902 (0.686)	0.649 (0.662)	0.822 (0.713)	0.953 (0.894)
IR2	-0.115	0.213 (0.020)	-0.455 (-0.242)	0.337 (0.112)	0.205 (-0.110)	-0.079 (-0.222)	0.018 (-0.167)	0.497 (0.092)
GRNRED	-0.585	-0.891 (-0.868)	-0.241 (-0.394)	0.426 (0.688)	-0.781 (-0.689)	-0.256 (-0.358)	-0.587 (-0.584)	-0.530 (-0.559)
GRNIR1	0.143	-0.006 (0.177)	0.425 (0.337)	-0.215 (-0.081)	-0.163 (0.080)	-0.061 (0.027)	-0.046 (0.147)	-0.545 (-0.182)
GRN1R2	0.743	0.465 (0.624)	0.867 (0.824)	-0.578 (-0.623)	0.447 (0.622)	0.549 (0.703)	0.613 (0.767)	0.062 (0.532)
REDIR1	0.359	0.384 (0.487)	0.437 (0.435)	-0.343 (-0.330)	0.157 (0.330)	0.010 (0.135)	0.168 (0.338)	-0.281 (0.043)

MSS band values used were the mean values for each of the nine lakes. Contact-sensed data were also mean values for each lake.

Table 4-21. Pearson Product-Moment Correlation Coefficients for 9 Colorado Lakes (August 1975 Contact-Sensed and Destriped MSS Data) (Continuation 1)

MSS Bands	PC1	CHLA (LNCHLA)	COND (LNCOND)	SEC (LNSEC)	ISEC (LNISEC)	TPHOS (LNTPHOS)	TON (LNTON)	AAY (LNAAY)
REDIR2	0.825	0.659 (0.788)	0.831 (0.840)	-0.622 (-0.735)	0.604 (0.734)	0.537 (0.708)	0.693 (0.833)	0.182 (0.614)
IR1IR2	0.870	0.606 (0.668)	0.722 (0.771)	-0.583 (-0.741)	0.710 (0.740)	0.723 (0.842)	0.804 (0.848)	0.531 (0.813)
PCIMSS	0.874	0.937 (0.900)	0.508 (0.729)	-0.462 (-0.790)	0.934 (0.791)	0.620 (0.681)	0.863 (0.831)	0.790 (0.875)

GRN - mean green DN level
RED - mean red DN level
IR1 - mean infrared - one DN level
IR2 - mean infrared - two DN level
GRNRED - green to infrared - one ratio
GRNIR1 - green to infrared - two ratio
REDIR1 - red to infrared - one ratio
REDIR2 - red to infrared - two ratio
IR1IR2 - infrared-one to infrared-two ratio

CHLA - chlorophyll a (ug/liter)
COND - conductivity (micromhos)
SEC - Secchi disc transparency (meters)
ISEC - inverse of Secchi disc transparency (1/meter)
TPHOS - Total phosphorus (milligrams/liter)
TON - total organic nitrogen (milligrams/liter)
AAY - algal assay control yield (milligram/liter dry wt.)

LN - natural logarithm transformation

PCI - trophic index values for lakes generated from principal component ordination analysis of 6 trophic indicators (LNCHLA, LNCOND, LNISEC, LNTPHOS, LNTON, LNAAY). August data used.

PC1MSS - "new" MSS variable generated by principal component analysis of the four MSS bands.

Table 4-22. Pearson Product-Moment Correlation Coefficients Generated from Landsat MSS and Trophic Indicator Data for 27 Sites Located in 9 Colorado Lakes[a,b,c]

MSS Bands	PC1	CHLA (LNCHLA)	COND (LNCOND)	SEC (LNSEC)	ISEC (LNISEC)	TPHOS (LNTPHOS)	TON (LNTON)	AAY (LNAAY)	PC1-27-53
GRN	0.838	0.590 (0.799)	0.640 (0.754)	-0.458 (-0.770)	0.731 (0.770)	0.519 (0.657)	0.730 (0.776)	0.487 (0.725)	0.850
RED	0.731	0.535 (0.740)	0.485 (0.581)	-0.379 (-0.710)	0.679 (0.709)	0.390 (0.524)	0.637 (0.707)	0.445 (0.627)	0.743
IR1	0.570	0.471 (0.574)	0.253 (0.415)	-0.174 (-0.509)	0.677 (0.511)	0.386 (0.414)	0.577 (0.526)	0.582 (0.584)	0.556
IR2	0.081	0.057 (0.167)	-0.085 (0.141)	0.1011 (-0.057)	0.198 (0.058)	-0.022 (-0.015)	0.076 (0.060)	0.151 (0.039)	0.090
GRNRED	-0.410	-0.352 (-0.516)	-0.129 (-0.149)	0.180 (0.474)	-0.456 (-0.475)	-0.121 (-0.238)	-0.366 (-0.459)	-0.280 (-0.323)	-0.425
GRNIR1	-0.039	-0.144 (-0.103)	0.213 (0.126)	-0.177 (0.024)	-0.257 (-0.026)	0.046 (0.024)	-0.145 (-0.076)	-0.325 (-0.124)	0.018
GRNIR2	0.437	0.324 (0.349)	0.471 (0.311)	-0.376 (-0.409)	0.236 (0.408)	0.352 (0.424)	0.378 (0.425)	0.143 (0.393)	0.438
REDIR1	0.236	0.082 (0.230)	0.333 (0.252)	-0.325 (-0.296)	0.023 (0.293)	0.030 (0.185)	0.089 (0.231)	-0.177 (0.084)	0.269
REDIR2	0.553	0.434 (0.512)	0.470 (0.351)	-0.405 (-0.545)	0.389 (0.544)	0.361 (0.472)	0.483 (0.555)	0.252 (0.489)	0.558

Table 4-22. Pearson Product-Moment Correlation Coefficients Generated from Landsat MSS and Trophic Indicator Data for 27 Sites Located in 9 Colorado Lakes[a,b,c] (Continuation 1)

MSS Bands	PC1	CHLA (LNCHLA)	COND (LNCOND)	SEC (LNSEC)	ISEC (LNISEC)	TPHOS (LNTPHOS)	TON (LNTON)	AAY (LNAAY)	PC1-27-53
IR1IR2	0.502	0.440 (0.441)	0.333 (0.257)	-0.299 (-0.469)	0.457 (0.469)	0.409 (0.443)	0.506 (0.490)	0.422 (0.537)	0.483
LNGRN	0.833	0.571 (0.787)	0.642 (0.763)	-0.463 (-0.768)	0.719 (0.767)	0.518 (0.649)	0.720 (0.768)	0.471 (0.714)	0.846
LNRED	0.736	0.531 (0.746)	0.491 (0.583)	-0.387 (-0.718)	0.678 (0.718)	0.401 (0.538)	0.640 (0.712)	0.435 (0.620)	0.751
LNIR1	0.557	0.458 (0.564)	0.260 (0.410)	-0.162 (-0.497)	0.641 (0.498)	0.365 (0.401)	0.557 (0.529)	0.534 (0.551)	0.547
LNIR2	0.096	0.061 (0.167)	-0.062 (0.168)	0.104 (-0.065)	0.207 (0.066)	-0.015 (-0.000)	0.085 (0.072)	0.155 (0.058)	0.104

[a] Destriped MSS data.

[b] 25 degrees of freedom. 0.05 level = 0.381, 0.01 level = 0.487.

[c] Trophic index for 27 sites developed from principal components analysis of five indicators: LNCHLA, LNISEC, LNCOND, LNTPHOS, and LNTON.

Table 4-23. Pearson Product-Moment Correlation Coefficients Between Landsat MSS Bands and Trophic Indicators for 13 Sampling Sites on 5 Colorado Lakes

Trophic Indicator	Landsat Band			
	GRN	RED	IR1	IR2
CHLA	0.584	0.521	0.592	0.148
LNCHLA	0.812	0.739	0.727	0.162
ISEC	0.763	0.700	0.907	0.516
LNISEC	0.847	0.769	0.692	0.159
SEC	-0.589	-0.488	-0.284	0.245
LNSEC	-0.847	-0.769	-0.690	-0.156
TPHOS	0.506	0.351	0.492	0.067
LNTPHOS	0.732	0.586	0.601	0.098
TON	0.783	0.655	0.793	0.278
LNTON	0.890	0.765	0.735	0.198
AAY	0.477	0.432	0.755	0.388
LNAAY	0.813	0.712	0.802	0.299
COND	0.650	0.477	0.288	-0.091
LNCOND	0.800	0.652	0.534	0.148
PC1-13	0.893	0.771	0.753	0.196

Table 4-24. Pearson Product-Moment Correlation Coefficients Generated from MMS and Trophic Indicator Data for 13 Sites Located in 5 Colorado Lakes[a,b,c]

MMS Channel	CHLA (LNCHLA)	COND (LNCOND)	SEC (LNSEC)	ISEC (LNISEC)	TPHOS (LNTPHOS)	TON (LNTON)	AAY (LNAAY)	TEMP °C	PC1-13	PC1-13-53
1 (370-413 nm)	0.652 (0.875)	0.708 (0.578)	-0.717 (-0.840)	0.625 (0.839)	0.547 (0.764)	0.750 (0.856)	0.304 (0.663)	0.838	0.842	0.872
2 (440-490 nm)	0.611 (0.806)	0.673 (0.585)	-0.722 (-0.803)	0.541 (0.802)	0.395 (0.652)	0.634 (0.784)	0.155 (0.557)	0.824	0.768	0.806
3 (495-535 nm)	0.609 (0.808)	0.694 (0.658)	-0.726 (-0.827)	0.585 (0.825)	0.411 (0.671)	0.664 (0.816)	0.188 (0.602)	0.867	0.801	0.836
4 (540-580 nm)	0.647 (0.877)	0.707 (0.710)	-0.750 (-0.910)	0.740 (0.907)	0.532 (0.767)	0.796 (0.908)	0.382 (0.752)	0.929	0.903	0.924
7 (660-700 nm)	0.632 (0.816)	0.475 (0.501)	-0.685 (-0.826)	0.627 (0.825)	0.263 (0.541)	0.596 (0.730)	0.263 (0.570)	0.792	0.733	0.761
8 (700-740 nm)	0.706 (0.910)	0.403 (0.442)	-0.673 (-0.888)	0.831 (0.889)	0.481 (0.675	0.787 (0.812)	0.632 (0.776)	0.773	0.835	0.837
9 (760-860 nm)	0.732 (0.856)	0.295 (0.223)	-0.618 (-0.766)	0.695 (0.766)	0.366 (0.549)	0.657 (0.659)	0.481 (0.582)	0.609	0.679	0.693
10 (970-1060 nm)	0.527 (0.431)	0.056 (-0.143)	-0.259 (-0.239)	0.117 (0.239)	-0.119 (0.055)	0.101 (0.135)	-0.192 (-0.080)	0.161	0.126	0.174
11 (8000-13000 nm)	0.428 (0.764)	0.873 (0.780)	-0.709 (-0.875)	0.715 (0.874)	0.706 (0.883)	0.826 (0.932)	0.402 (0.813)	0.958	0.923	0.934

[a] Barr R., Cherry Creek R., Grand L., Dillon R., and Milton R.

[b] 11 degrees of freedom. 0.05 level = 0.553; 0.01 level = 0.684.

[c] Trophic index for 13 sites developed from principal components analysis of five trophic indices: LNCHLA, LNISEC, LNCOND, LNTPHOS, and LNTON.

Table 4-25. Pearson Product-Moment Correlation Coefficients Generated from Principal Component-Derived MMS Variable and Trophic Indicator Data for 13 Sampling Sites in 5 Colorado Lakes

MMS Variable	CHLA (LNCHLA)	COND (LNCOND)	SEC (LNSEC)	ISEC (LNISEC)	TPHOS (LNTPHOS)	TON (LNTON)	AAY (LNAAY)	PC1-13
MMSPC1	0.656 (0.863)	0.663 (0.612)	-0.740 (-0.863)	0.646 (0.862)	0.448 (0.700)	0.712 (0.840)	0.277 (0.648)	0.831
MMSPC2	0.357 (0.294)	-0.422 (-0.424)	-0.019 (-0.143)	0.336 (0.144)	-0.017 (-0.031)	0.152 (-0.010)	0.465 (0.131)	0.038
MMSPC3	0.008 (-0.166)	-0.047 (-0.359)	0.108 (0.330)	-0.541 (-0.332)	-0.380 (-0.316)	-0.428 (-0.350)	-0.732 (-0.608)	-0.390
MMSPC4	-0.077 (-0.201)	-0.447 (-0.183)	0.078 (0.123)	-0.191 (-0.125)	-0.726 (-0.560)	-0.470 (-0.353)	-0.362 (-0.379)	-0.334
MMSPC5	0.179 (0.044)	0.152 (0.308)	-0.067 (-0.085)	0.205 (0.086)	-0.003 (0.039)	0.132 (0.113)	-0.071 (0.053)	0.108
MMSPC6	0.232 (0.161)	-0.050 (0.034)	0.265 (-0.029)	0.210 (0.030)	-0.218 (-0.108)	0.029 (0.034)	-0.131 (-0.053)	0.016
MMSPC7	0.336 (0.066)	-0.168 (0.155)	0.434 (0.239)	-0.041 (-0.238)	-0.075 (-0.067)	0.038 (-0.015)	0.091 (0.005)	-0.025
MMSPC8	0.058 (0.046)	-0.234 (-0.142)	-0.257 (-0.099)	-0.028 (0.098)	-0.214 (-0.192)	-0.132 (-0.122)	-0.055 (-0.043)	-0.061

D. REGRESSION MODELS FOR THE ESTIMATION OF TROPHIC INDICATORS AND MULTIVARIATE TROPHIC INDICATORS

Regression models were developed for the estimation of CHLA, ISEC, SEC, TPHOS, TON, COND, AAY, and three principal component-derived trophic state indices, PC1-11, PC1-27, and PC1-13 (Table 4-26). It is noted that the models are grouped by dependent variable (e.g., CHLA) with each group consisting of one to seven models. The comments column in Table 4-26 provides information explaining some factors on which the models are based. This can be illustrated by examining the comments made regarding the models for ISEC (models 7 to 13, inclusive):

(1) Model 7. The four Landsat bands were treated as independent variables during the interactive model development phase. The final model incorporates a single independent, the Landsat RED band. The MSS values used for modeling purposes consisted of averages for each band for each of nine Colorado lakes. The dependent variable values, ISEC (actually its natural logarithm transformed version), were means for each of the same nine lakes. Landsat band ratios were also considered as independent variables.

(2) Model 8. As with Model 7, the four Landsat bands and their ratios were examined during the multiple regression procedure; the final model incorporates only the Landsat GRN band. In this particular case, the values of the dependent and independent variables were means calculated for each of 27 sites located on 9 Colorado lakes. This is in contrast to Model 7 in which the same 9 lakes were treated as "whole" water bodies.

(3) Model 9. The four Landsat bands and their ratios were employed in the modeling effort. The data values were means for each of 13 sampling sites on 5 Colorado lakes. These sites are included in the 27 sites discussed above and are the same sites used in the development of the models discussed next (10, 11, 13, and 13).

(4) Model 10. In this case, eight MMS channels (2 of the 11 channels were missing and it was not deemed appropriate to include the thermal channel, CH11) were treated as independent variables during the model development phase; no channel ratios were employed. The data values were averages for each of 13 sites on 5 Colorado lakes.

(5) Model 11. The same data and sites were employed as in the developmental phase of model 10. However, the selection of the independent variables was limited to channels 4, 7, 8, and 9. This was an effort to mimic the bands found in the Landsat MSS.

Table 4-26. Regression Models Developed from Contact, MSS and MMS Data

Model Number	Dependent Variable	Intercept Value	Independent Variables and Associated Coefficients	Regression, Residual d.f.	Calculated F-value	R^2x100	Standard Error of Estimate	Comments
CHLA								
1	LNCHLA	-3.036	+0.233 RED	1, 7	64.87	90.26	3.2	9 lakes. Landsat MSS
2	LNCHLA	-3.367	+0.142 GRN	1, 25	44.07	63.80	21.6	27 sites. Landsat MSS
3	LNCHLA	0.728	+0.449 IR1; -1.039 IR2	2, 10	15.35	75.43	28.7	13 sites. Landsat MSS
4	LNCHLA	-25.628	+0.358 CH1; -0.220 CH2; +0.207 CH7	3, 9	20.49	87.23	23.0	13 sites. MMS. 8 channel selection
5	LNCHLA	-9.281	+0.081 CH4; +0.156 CH9	2, 10	30.71	86.00	18.0	13 sites. MMS. Channel selection limited to 4,7,8,9
6	LNCHLA	-12.901	+0.059 MMSPC1; +0.001 MSSPC2	2, 10	24.69	83.16	17.4	13 sites. MMS. 8 principal component-derived "new" channels
ISEC								
7	LNISEC	-3.931	+0.150 RED	1, 7	13.76	66.28	0.272	9 lakes. Landsat MSS
8	LNISEC	-4.817	+0.112 GRN	1, 25	36.34	59.25	0.660	27 sites. Landsat MSS
9	LNISEC	-5.811	+0.135 GRN	1, 11	27.92	71.73	0.629	13 sites. Landsat MSS
10	LNISEC	-8.120	+0.119 CH4	1, 11	52.78	82.75	0.717	13 sites. MMS. 8 channel selection
11	LNISEC	-8.120	+0.119 CH4	1, 11	52.78	82.75	0.717	13 sites. MMS. Channel selection limited to 4,7,8,9
12	LNISEC	9.474	+0.51 MMSPC1; -0.115 MMSPC3; -1.519 MMSPC7	3, 9	30.23	90.97	0.620	13 sites. MMS. 8 principal component derived "new" channels

Table 4-26. Regression Models Developed from Contact, MSS and MMS Data (Continuation 1)

Model Number	Dependent Variable	Intercept Value	Independent Variables and Associated Coefficients	Regression, Residual d.f.	Calculated F-value	R^2x100	Standard Error of Estimate	Comments
ISEC								
13	LNISEC	-6.165	+0.051 MMSPC1; -0.115 MMSPC3	2, 10	29.11	85.34	0.636	13 sites. MMS. Selection limited to first 4 components of principal component transformed 8 channels
SEC								
	LNSEC		(Model development not attempted)					9 lakes. Landsat MSS
	LNSEC		(Model development not attempted)					27 sites. Landsat MSS
	LNSEC		(Model development not attempted)					13 sites. Landsat MSS
	LNSEC		(Model development not attempted)					13 sites. MMS
14	LNSEC	8.119	-0.119 CH4	1, 11	53.24	82.88	2.59	13 sites. MMS. Channel selection limited to 4,7,8,9
15	LNSEC	-9.520	-0.051 MMSPC1; +0.114 MMSPC3; +1.527 MMSPC7	3, 9	30.78	91.12	1.50	13 sites. MMS. 8 principal component-derived "new" channels
16	LNSEC	6.196	-0.051 MMSPC1; +0.114 MMSPC3	2, 10	29.29	85.42	2.55	13 sites. MMS. Selection limited to first 4 components of principal component transformed 8 channels
TPHOS								
17	LNTPHOS	-3.746	+0.575 IR1; -1.301 IR2	2, 6	7.63	71.75	0.215	9 lakes. Landsat MSS
18	LNTPHOS	-10.053	+0.176 GRN	1, 25	18.26	41.84	0.237	27 sites. Landsat MSS

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Table 4-26. Regression Models Developed from Contact, MSS and MMS Data (Continuation 2)

Model Number	Dependent Variable	Intercept Value	Independent Variables and Associated Coefficients	Regression, Residual d.f.	Calculated F-value	R^2x100	Standard Error of Estimate	Comments
TPHOS								
19	LNTPHOS	-10.785	+0.201 GRN	1, 11	12.70	53.59	0.323	13 sites. Landsat MSS
20	LNTPHOS	-16.360	+0.462 CH2; -0.768 CH3; +0.712 CH4 -0.462 CH7	4, 8	16.64	89.27	0.284	13 sites. MMS. 8 channel selection
21	LNTPHOS	-8.947	+0.437 CH4; -0.463 CH7	2, 10	20.53	80.42	0.198	13 sites. MMS channel selection limited to 4,7,8,9
22	LNTPHOS	-28.507	+0.071 MMSPC1; -0.190 MMSPC3; -0.559 MMSPC4	3, 9	28.38	90.44	0.171	13 sites. MMS. 8 principal component-derived "new" channels
TON								
23	LNTON	-6.511	+0.143 GRN	1, 7	25.99	78.78	0.268	9 lakes. Landsat MSS
24	LNTON	-5.367	+0.113 GRN	1, 25	37.94	60.28	0.317	27 sites. Landsat MSS
25	LNTON	-5.363	+0.118 GRN	1, 11	41.83	79.18	0.410	13 sites. Landsat MSS
26	LNTON	-4.793	-0.091 CH3; +0.253 CH4; -0.104 CH7	3, 9	58.23	95.10	0.116	13 sites. MMS. 8 channel selection
27	LNTON	-6.449	+0.167 CH4; -0.190 CH7; +0.076 CH8	3, 9	59.69	95.21	0.091	13 sites. MMS channel selection limited to 4,7,8,9
28	LNTON	-10.732	+0.041 MMSPC1; -0.101 MMSPC3; -0.170 MMSPC4	3, 9	59.80	95.22	0.176	13 sites. MMS. 8 principal component-derived "new" channels
COND								
29	LNCOND	-11.690	+0.882 GRN; -0.807 RED	2, 6	29.53	90.78	120	9 lakes. Landsat MSS

Table 4-26. Regression Models Developed from Contact, MSS and MMS Data (Continuation 3)

Model Number	Dependent Variable	Intercept Value	Independent Variables and Associated Coefficients	Regression, Residual d.f.	Calculated F-value	R^2x100	Standard Error of Estimate	Comments
COND								
30	LNCOND	-6.277	+0.493 GRN; -0.360 RED	2, 24	31.38	72.33	271	27 sites. Landsat MSS
31	LNCOND	-2.618	+0.201 GRN	1, 11	19.46	63.89	4390	13 sites. Landsat MSS
32	LNCOND	2.251	+0.255 CH4; -0.326 CH9	2, 10	12.85	72.00	462	13 sites. MMS. 8 channel selection
33	LNCOND	2.251	+0.255 CH4; -0.326 CH9	2, 10	12.85	72.00	462	13 sites. MMS channel selection limited to 4,7,8,9
34	LNCOND	-6.412	+0.057 MSSPC1	1, 11	6.57	38.40	444	13 sites. MMS. 8 principal component-derived "new" channels
AAY								
35	LNAAY	-6.285	+0.823 IR1; -0.954 IR2	2, 6	21.37	87.69	15.7	9 lakes. Landsat MSS
36	LNAAY	-7.481	+0.190 GRN; +0.246 IR1; -0.634 IR2	3, 23	13.84	64.35	44.9	27 lakes. Landsat MSS
37	LNAAY	-13.288	+0.439 GRN; -0.376 RED; +0.392 IR1	3, 9	15.21	83.53	46.9	13 sites. Landsat MSS
38	LNAAY	-12.273	+0.289 CH4; -0.654 CH7; +0.835 CH8 -0.460 CH9	4, 8	39.22	95.15	30.1	13 sites. MSS. 8 channel selection
39	LNAAY	-12.273	+0.289 CH4; -0.654 CH7; +0.835 CH8 -0.460 CH9	4, 8	39.22	95.15	30.1	13 sites. MMS channel selection limited to 4,7,8,9
40	LNAAY	-12.841	+0.081 MMSPC1; -0.446 MMSPC3; -0.462 MMSPC4	3, 9	41.32	93.23	24.8	13 sites. MMS. Eight principal component-derived "new" channels

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Table 4-26. Regression Models Developed from Contact, MSS and MMS Data (Continuation 4)

Model Number	Dependent Variable	Intercept Value	Independent Variables and Associated Coefficients	Regression, Residual d.f.	Calculated F-value	R^2x100	Standard Error of Estimate	Comments
PC1-11								
41	PC1-11	-5.359	+0.218 RED; +0.421 IR1; -1.036 IR2	3, 5	21.06	92.67	0.67	9 lakes. Landsat MSS
PC1-27								
42	PC1-27	-12.414	+0.331 GRN	1, 25	59.59	70.45	1.19	27 sites. Landsat MSS
PC1-13								
43	PC1-13	-13.153	+0.539 GRN; -0.442 RED; +0.632 IR1 -1.332 IR2	4, 8	33.22	94.32	0.86	13 sites. Landsat MSS
44	PC1-13	-12.617	-0.476 CH3; +0.797 CH4	2, 10	68.14	93.16	0.84	13 sites. MMS. 8 channel selection.
45	PC1-13	-17.912	+0.480 CH4; -0.595 CH7; +0.305 CH8	3, 9	60.89	95.30	0.86	13 sites. MMS. Channel selection limited to 4,7,8,9
46	PC1-13	-27.289	+0.126 MMSPC1; -0.348 MMSPC3; -0.497 MMSPC4	3, 9	62.93	95.45	0.73	13 sites. MMS. Selection limited to first 4 component of principal component transformed 8 channels

(6) Model 12. As was noted in the preceding subsection on interband and interchannel correlations, the correlative problem is substantial. An attempt was made to circumvent this situation, in the case of the MMS channels, by generating "new" independent or orthogonal variables (MMSPC1, ... , MMSPC8) through principal components analysis. During the development of Model 12, these "new" variables were treated as independent variables. The dependent and independent variable values were means for each of the 13 sites on the 5 lakes.

(7) Model 13. The same basic approach was used as in the development of Model 12. However, the selection of independent variables was limited to the first four "new" variables generated by the principal component analysis of the eight MMS channels. These components (MMSPC1, ..., MMSPC4) account for about 99.54% of the variation in the eight-channel MMS data available for the 13 sites.

As is evident from Table 4-26, some models were not developed for SEC. It was determined that to do so would be to needlessly repeat the development of the ISEC models, but in an inverse way. The actual, estimated, and residual values for the dependent variables found in Models 1 to and including 46 are in Appendix C.

An examination of Table 4-26 indicates that the Landsat-derived models incorporate only the MSS bands as the independent variables. The aircraft-borne MMS-derived models utilize either the MMS channels (excluding CH5, CH6, and CH11) or "new" variables generated through the principal component analysis of CH1, CH2, CH3, CH4, CH7, CH8, CH9, and CH10. The development of regression models employing Landsat MSS bands or MMS channels as independent variables for the estimation of a variety of water quality parameters is not new. Several investigators have also used MSS band ratios in attempts to reduce the magnitude of the atmospheric effects.

Yarger and McCauley (1975), reporting on an investigation to determine the feasibility of developing quantitative estimates of water quality in Kansas reservoirs, employed Landsat MSS ratios in their regression models. They indicate that (1) MSS ratios were very effective in providing quantitative estimates of suspended solids up to at least 900 ppm; (2) significant correlations were not found between Landsat MSS data and dissolved solids, potassium, phosphate, and nitrate, at least at the levels found in the Kansas reservoirs, and the Landsat RED/GRN ratio correlates weakly with total chlorophyll levels above approximately 8 μg/liter.

Rogers et al. (1976) have developed regression models for prediction of several water quality indicators in Saginaw Bay (Michigan). Their models contain the following Landsat MSS band and band ratios as independent variables:

(1) Temperature (°C) - RED.
(2) Secchi depth (m) - RED.

(3) Chloride (mg/liter) - GRN/RED.
(4) Conductivity (μmhos/cm) - GRN/RED.
(5) Total Kjeldahl nitrogen (mg/liter) - GRN/RED.
(6) Total phosphorus (mg/liter) - GRN/RED.
(7) Chlorophyll a (μg/liter) - GRN/RED.

They report the addition of other independent variables into the models did not improve the regression correlation coefficient significantly.

Boland (1976) has also described the use of Landsat MSS ratios as independent variables in regression models for prediction of trophic indicator magnitudes. Attempts to use MSS ratios in the development of regression models for the Colorado lakes were less successful than efforts using the MSS bands' raw values.

Ideally, each regression model would have an R^2 of 100% and a standard error of estimate of 0. An examination of the models in Table 4-26 indicates that all fall short of the ideal. This is not surprising since in the area of environmental studies there tends to be much variation in data and the attainment of very high R^2 (e.g., > 95%) is the exception rather than the rule. A few general comments can be made about the models.

(1) As the number of observations increases, the R^2 decreases and the estimate of standard error increases. Model 1-3 and 7-9 are examples of the phenomenon. The estimates for the nine "whole" lakes are much better than those for the 27 sites located on the same lakes. The loss in accuracy may be related to factors such as sensor "noise" and the relatively small range of DN values compared to those of the trophic indicators.

(2) The dependent variables in the final models for a specific parameter (e.g., LNCHLA) and developed from a particular sensor's data (e.g., Landsat MSS) are sometimes different and appear related to the sampling sites included in model development. For example, in Model 1 for CHLA, RED is the dependent variable and in Model 2, GRN is the dependent variable; the 27 sites are on the 9 lakes. This suggests that model development is very sensitive to the sampling sites selected for calibration purposes.

(3) Some of the models for different parameters employ the same dependent variable(s) (e.g., Model 1 and Model 7), differing in their slope, intercept, and associated parameters. This is not surprising because, in general, the trophic indicators are correlated.

(4) In general, the models incorporating the principal component transformed MMS data provide slightly better results as measured by the R^2 and standard error of estimate values than those developed using the raw MMS data.

(5) Overall, the MSS and MMS data provide better estimates of the multivariate indices than of the individual trophic indicators. This may be a consequence of the relatively small range of the multivariate index values.

(6) A comparison of the models developed using ground truth from the 13 sites indicates that, as measured by the R^2 and standard error of estimate values, the aircraft-acquired MMS data provide better estimates of the trophic indicators and multivariate index examined here. This outcome may be a consequence of the MMS's greater spectral and spatial resolution and/or the lower altitude of the aircraft (i.e., atmospheric effects of a lesser magnitude) compared to that of Landsat and its MSS.

(7) The models may yield grossly inaccurate estimations when applied to water bodies from other regions or when applied to the same lake populations using MSS data from another period of time.

While the regression approach is attractive the user is confronted by several problems including:

(1) The prospect of data non-normality. This occurs frequently in inland lake water quality studies.

(2) Statistically significant correlations between MSS bands or MMS channels. This reduces the predictive value of some bands or channels.

(3) The relatively small range of MSS and MMS DN values compared to the ranges trophic indicator values often encountered in surveys involving large numbers of lakes. This makes it impossible to get accuracies and precisions obtainable through contact sensing.

The investigator can reduce the magnitude of the first problems by employing data transformation techniques which will induce a sense of normality. Mueller (1972) has demonstrated the use of principal component analysis to achieve orthogonality between variables. It is unclear from the study reported here as to what advantage was gained by generating "new" variables through the principal components analysis of the MMS channels. It appears that some consideration should be given to the use of class intervals for the trophic indicators because the user will often be confronted with the problem of the limited dynamic ranges of the MSS and MMS relative to the ranges of the ground truth parameters.

E. THEMATIC MAPPING RESULTS

The purpose of the following classification maps is to visually illustrate the relative lake rankings on a eutrophic-oligotrophic scale, employing either a multivariate index or a single trophic indicator. The maps serve as a visual aid in determining (1) the different trophic levels within a lake, (2) the locations of these different levels of trophy, and (3) the positional relationships of the different levels of trophy with each other and in comparison to the other lakes.

In determining the accuracy of a classification map it is important to be aware of certain factors. The horizontal bands which occasionally appear in the lake surface and are visually denoted by a continuous stripe of color are not to be interpreted as trophic features. In this Landsat imagery these are caused by residual sixth line banding which was not removed. The extreme sensitivity of the Bayesian Classifier causes the residual striping to appear due to the algorithm's ability to detect relatively small differences in data. As such, the stipes are an unfortunate artifact caused by the sensors and are not lacustrine features. When interpreting the accuracy of the clasification maps, one key is to look for uniform shading of colors from blues to greens, class to class. Uniform shading would tend to uphold the classification results as would large contiguous areas of color. A sudden jump from one class to another quite far down the relative trophic scale may suggest an error in the classification. However, this in not always the case as discrete water type boundaries may exist.

Classification accuracy can further be examined, in the following pages under the discussion of individual classification maps, through an interpretation of the "classification analysis" tables listed with each map. The tables enumerate the number of classes specified in a trophic classification and the percentage of pixels which were classified as belonging to each particular class. Ideally, the analyst would wish to see 100% accuracy across the diagonal of the classification analysis table, but with Landsat data expecially, this is rarely the case.

Six color thematic maps have been chosen to represent the range of trophic classifications attempted during the course of this project. Both Landsat-acquired and aircraft-acquired contact-sensed data were utilized in the classifications presented. All classifications were based on this sensor-acquired data in relationship to the water quality measurements taken by EPA personnel.

Individual water quality parameters, such as chlorophyll a and inverse Secchi disc, as well as combined parameters derived through the principal components ordination method were mapped and are illustrated on the following pages. The 13-site multivariate trophic index results will be examined first.

1. Trophic Classification of Five Colorado Lakes Based on 13-site Multivariate Index (PC1-13)

Figures 4-2 and 4-3 depict the spatial aspects of the trophic classification of 5 Colorado lakes based on Landsat MSS data and aircraft MMS data respectively. The number of lakes classified was reduced from 9 to 5 due to the unavailability of aircraft sensed data for Barker Reservoir, Green Mountain Reservoir, Shadow Mountain Reservoir and Blue Mesa Reservoir.

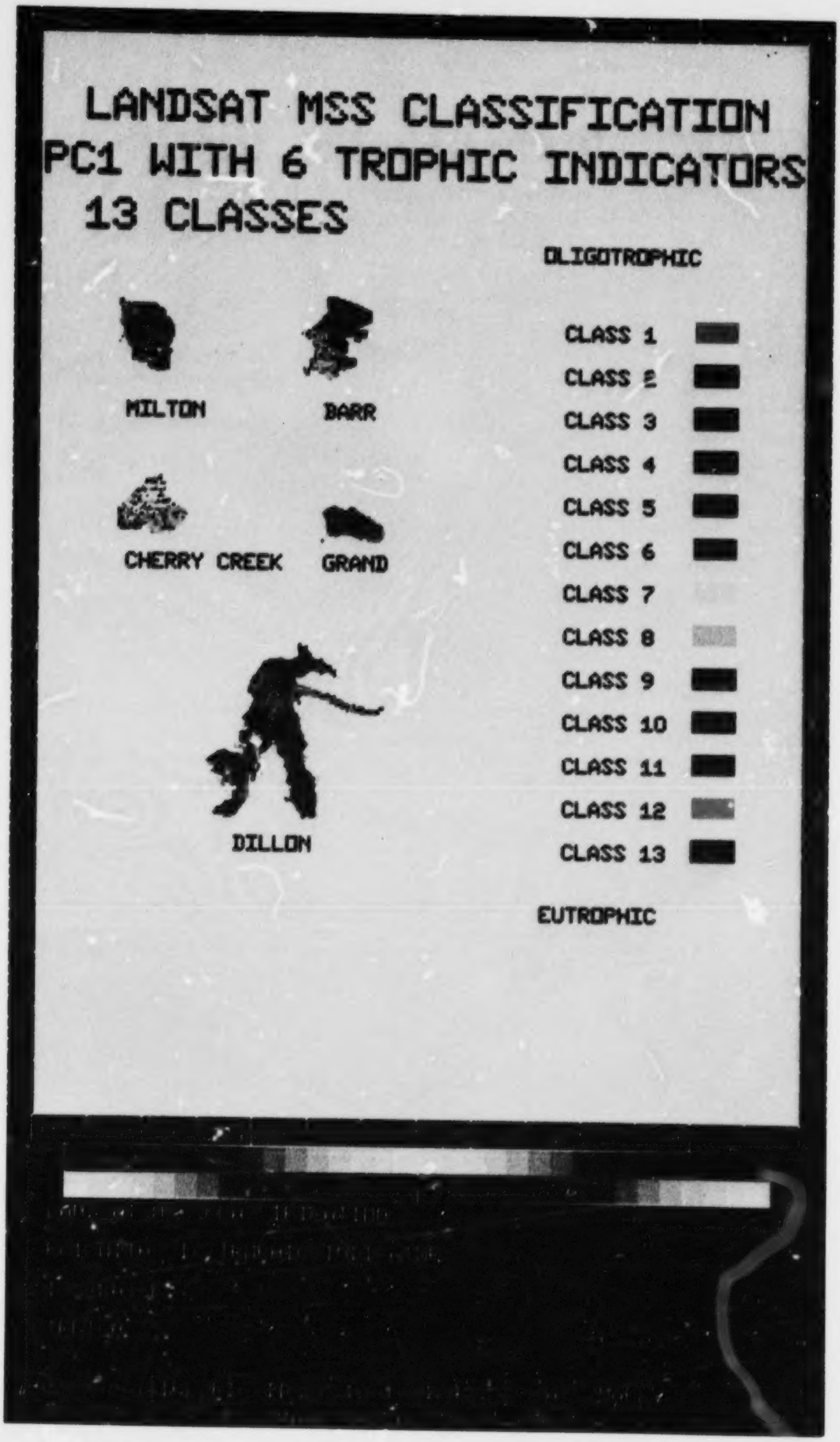
LANDSAT MSS CLASSIFICATION
PC1 WITH 6 TROPHIC INDICATORS
13 CLASSES
OLIGOTROPHIC
MILTON
BARR
CHERRY CREEK
GRAND
DILLON
CLASS 1
CLASS 2
CLASS 3
CLASS 4
CLASS 5
CLASS 6
CLASS 7
CLASS 8
CLASS 9
CLASS 10
CLASS 11
CLASS 12
CLASS 13
EUTROPHIC

Figure 4-2. Trophic Classification Maps of Five Colorado Lakes Based on Landsat-1 MSS Data and a Multivariate Trophic Index for 13 Sampling Sites (PC1-13)

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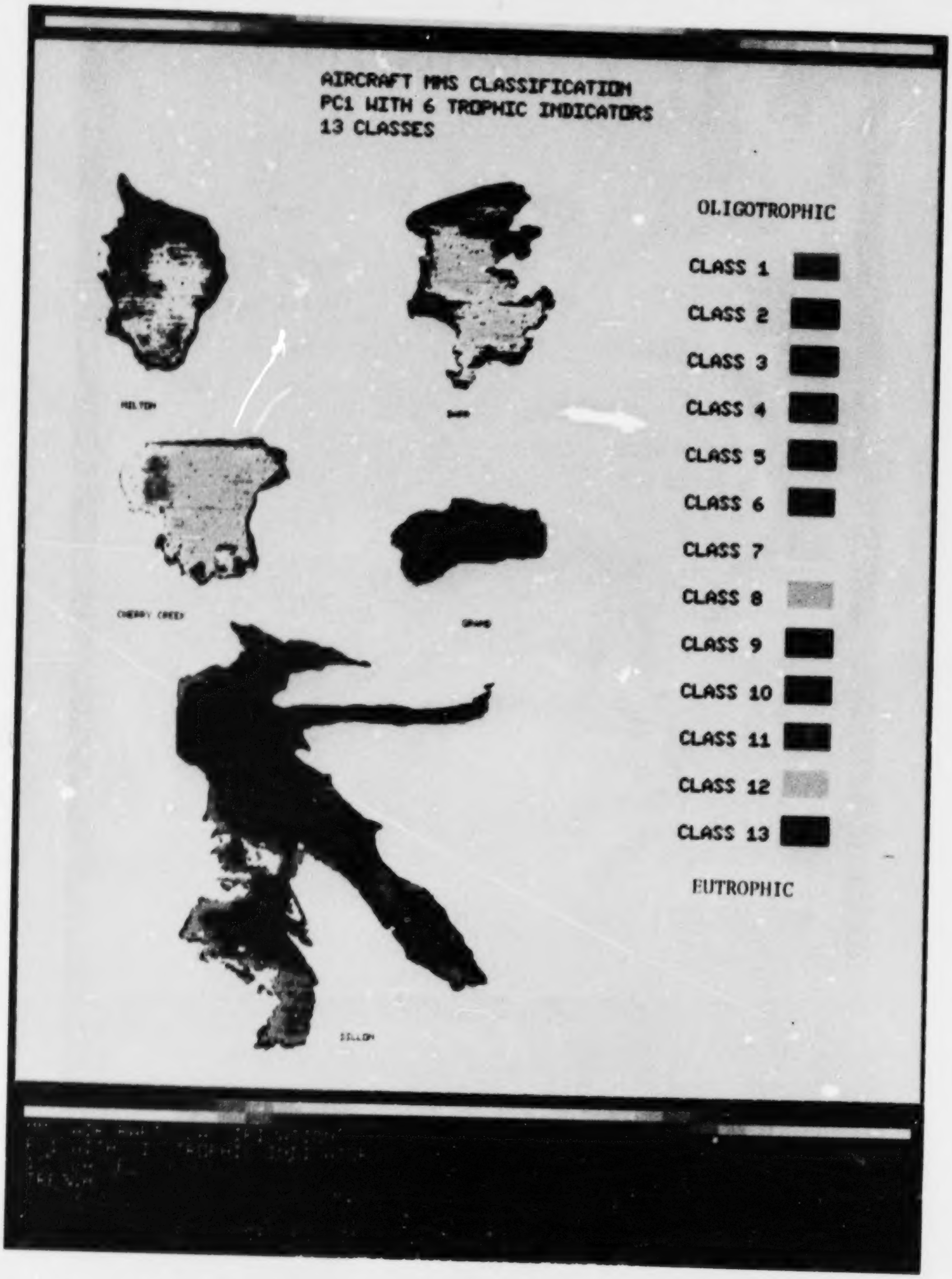
AIRCRAFT MMS CLASSIFICATION
PC1 WITH 6 TROPHIC INDICATORS
13 CLASSES
OLIGOTROPHIC
CLASS 1
CLASS 2
CLASS 3
CLASS 4
CLASS 5
CLASS 6
CLASS 7
CLASS 8
CLASS 9
CLASS 10
CLASS 11
CLASS 12
CLASS 13
EUTROPHIC
MILTON
CHERRY CREEK
DILLON

Figure 4-3. Trophic Classification Maps of Five Colorado Lakes Based on MMS Data and a Multivariate Trophic Index for 13 Sampling Sites (PC1-13)

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Each of the 13 sampling sites served as a trophic class (PC1-13) training site for both the Landsat MSS and MMS. In other words, parallel classification efforts were made using the maximum likelihood algorithm, one employing MSS data and the other MMS data. The training site classification results are compiled in Table 4-27. The computer classified 68 percent of the MSS pixels in Class 1 as having spectral properties characteristic of Class 1. Ideally it would have classified 100 percent of the pixels as belonging to Class 1.

Similarly 80% of the MMS pixels which served as Class 1 training sites were classified as Class 1. In general, MMS training site classification results are better than those of the Landsat MSS. Overall, approximately 83% of the MMS pixels were recognized as belonging in the proper class as compared to 63% of the Landsat pixels. Landsat training site classification accuracies range from 28% for Class 6 to 100% for Class 13. MMS accuracies range from about 64% for Class 12 to 99% for Class 9.

Table 4-28 displays the results of extending both Landsat MSS and MMS site-related trophic class signatures to all of the pixels in each of the five lakes. Though not identical, MSS and MMS results tend to follow the same general pattern. Based on the results of the site classification (Table 4-27), it follows that the MMS gives a more representative "picture" of the trophic status of the five lakes.

While the color-coded maps can be of practical values to limnologists, it must be kept in mind that several of the training sites were relatively heterogeneous, resulting in low site classification accuracies. Inclusion of such classes can adversely affect the lake classification results.

Ideally, each training site should be homogenous and spectrally separable from the other sites. Each site would then be spectrally unique for its multivariate trophic index value (i.e., have a spectral signature). If the above criteria of homogeneity and separability are not met, then the investigator should consider selecting different training sites and/or pooling some of those currently used. Generally the procedure is one of trial and error, guided by training site statistical information and the investigator's knowledge about the water bodies. It appears that some of the PC1-13 classes should be pooled.

2. Trophic Classification of Nine Colorado Lakes Based on a Pooled Multivariate Index (PC1-27)

The color map, Figure 4-4, depicts the results of the classification of nine Colorado lakes using Landsat MSS data. The classification was based on the trophic ranking of 27 sampling sites derived from principal components ordination. By using principal components analysis a single numerical expression representing 6 trophic indicators was derived. The 6 trophic indicators used were chlorophyll a, inverse Secchi disc, conductivity, total phosphorus, total organic nitrogen and algal assay yield. Table 4-29 lists the PC1 values for these 27 sampling sites as derived from principal components analysis. For classification, the PC1 values were ranked on a relative trophic scale and grouped into classes by identifying natural groupings in the numerical values.

Table 4-27. Landsat MSS and Bendix MMS Training Site Classification Accuracies Expressed as a Percentage of Each Site's Pixel Count

		Class												
Class	Sensor	1	2	3	4	5	6	7	8	9	10	11	12	13
1	MSS	68.0	4.0	4.0	16.0	8.0								
	MMS	80.1	10.7		5.7	3.3								
2	MSS	4.0	52.0	12.0	20.0		12.0							
	MMS	14.0	85.9											
3	MMS	14.0	12.0	52.0	20.0	4.0	12.0							
	MMS			92.5			7.4							
4	MSS	20.0	12.0	16.0	36.0		16.0							
	MMS	5.7		1.6	82.6	9.0	0.8							
5	MSS	8.0		4.0		88.0								
	MMS	2.4			16.5	80.9								
6	MSS	12.0	16.0	24.0	12.0	8.0	28.0							
	MMS			12.3			85.9			0.8		0.8		
7	MSS							92.0	4.0		4.0			
	MMS							66.9	12.3	2.4	2.4		0.8	14.8
8	MSS							4.0	48.0		4.0	20.0	24.0	
	MMS							10.7	83.4				4.1	1.6
9	MSS					12.0		8.0		80.0				
	MMS							0.8		99.1				
10	MSS							8.0		8.0	76.0	4.0	4.0	
	MMS							17.3		0.8	81.8			
11	MSS							20.0	4.0		4.0	40.0	32.0	
	MMS							4.1				95.0		0.8
12	MSS							4.0	12.0		8.0	16.0	60.0	
	MMS							19.0	12.3			1.6	63.6	3.3
13	MSS													100.0
	MMS							12.3		0.8			6.6	81.0

Percentage values of less than 0.05% are represented by empty matrix cells.
The Landsat MSS training sites samples generally consisted of 25 pixels (5 x 5 matrix). The MMS training site samples consisted of 121 pixels (11 x 11 matrix).

Table 4-28. Landsat MSS and Bendix MMS Lake Classification Results Expressed as a Percentage of Each Lake's Pixel Count

Class Num-ber	PC1-13 Value	Site Storet Numer	Dillon		Grand		Cherry Creek		Milton		Barr	
			MSS	MMS	MSS	MMS	MSS	MMS	MSS	MMS	MSS	MMS
1	-2.46	080603	35.63	26.83	26.76	0.05			1.37		0.30	
2	-2.31	080604	10.01	28.29	8.30							
3	-2.18	080702	10.01	4.82	28.00	32.05		0.43				
4	-2.07	080602	11.17	24.11	6.46	0.16						
5	-2.07	080701	16.73	11.98	6.46				7.53			
6	-2.05	080601	5.36	3.63	19.07	65.95		0.29				
7	0.57	080401	6.19	0.01		0.07	30.56	24.17	6.33	35.39	1.23	24.69
8	0.89	080403	1.78	0.01	4.30	0.20	16.63	43.72	4.11	2.40	13.44	8.85
9	1.55	081101	0.91	0.00[a]	0.30	0.15	0.19	3.71	34.41	31.60	0.77	7.41
10	1.93	081102	0.38			0.15	11.99	1.82	25.51	16.72	6.49	0.01
11	1.94	080402	0.04	0.26		1.04	16.63	8.68	8.04		14.21	1.52
12	2.78	080202	0.74	0.01		0.07	20.50	6.94	7.36	0.29	14.83	22.49
13	3.47	080201		0.01	0.30	0.08	3.48	10.21	5.30	13.58	48.68	35.00

Percentage values of less than 0.05% are represented by empty matrix cells.

[a] Less than 0.005%.

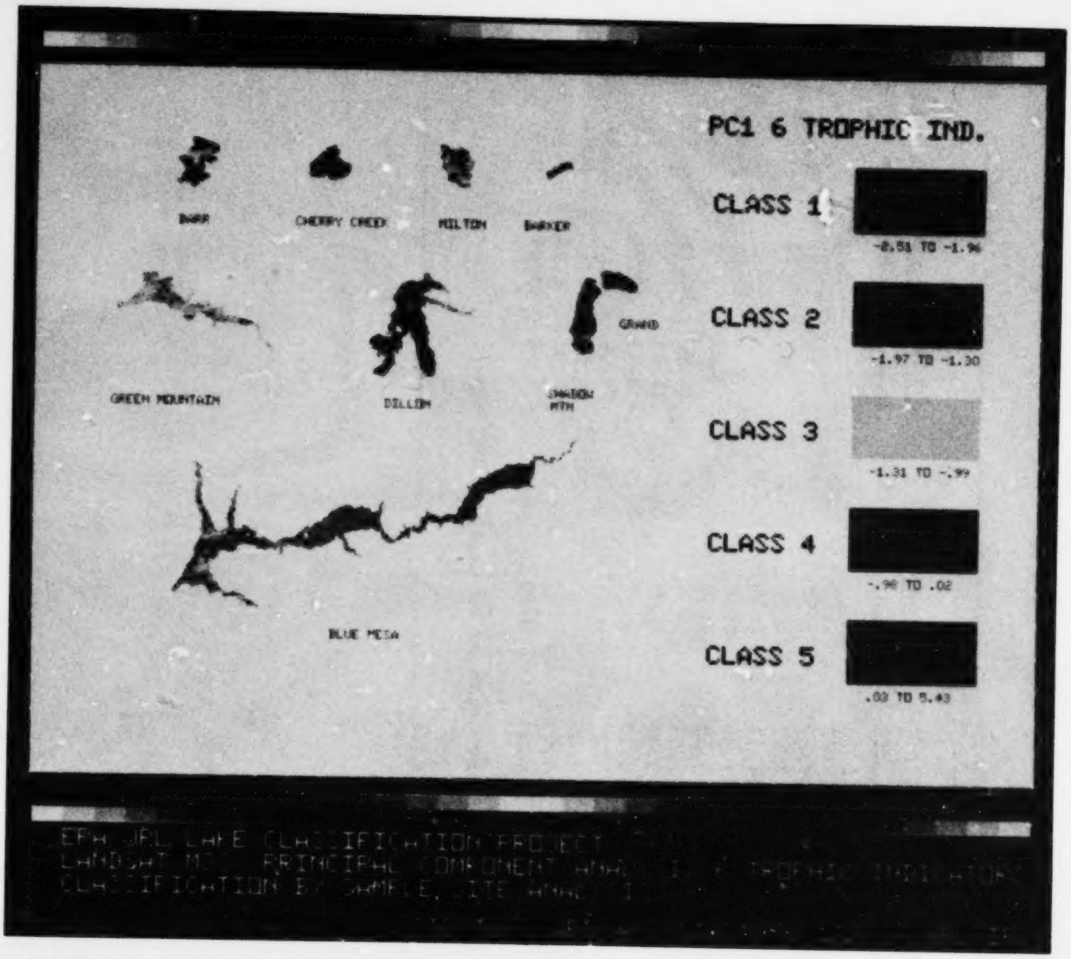
PC1 6 TROPHIC IND.
CLASS 1
-2.51 TO -1.96
CLASS 2
-1.97 TO -1.30
CLASS 3
-1.31 TO -.99
CLASS 4
-.98 TO .02
CLASS 5
.03 TO 5.43
BARR
CHERRY CREEK
MILTON
BARKER
GREEN MOUNTAIN
DILLON
SHADOW MTN
GRAND
BLUE MESA
EPA JPL LAKE CLASSIFICATION PROJECT
LANDSAT MSS PRINCIPAL COMPONENT ANAL. 6 TROPHIC INDICATORS
CLASSIFICATION BY SAMPLE SITE ANAL.

Figure 4-4. Trophic Classification of Nine Colorado Lakes Based on a Pooled Multivariate Index (PC1-27)

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Table 4-29. Classification Analysis of Nine Colorado Lakes Based on a Pooled Multivariate Index (PC1-27)

	Percent Classified as						
Class	0*	1	2	3	4	5	Ambiguous
1	0.0	76.0	19.0	2.0	3.0	0.0	0.0
2	0.0	24.0	68.0	0.0	8.0	0.0	0.0
3	0.0	0.0	0.0	90.2	4.8	4.8	0.0
4	0.0	7.5	42.6	13.3	34.2	2.2	0.0
5	0.0	0.0	1.7	13.7	1.7	82.8	0.0

*Undefined classification

A total of five classes were selected for this particular classification. Table 4-29 enumerates the classification accuracy in terms of percent of pixels actually assigned to a particular class. Ideally, each cell on the matrix diagonal would contain a value of 100 indicating that all of the pixels within a particular training site (in this case pooled training sites) were identified by the classification program as being in the class for which they provided the calibration data. Class 4 with a classification percentage of 34.2 is a highly suspect class; 42.6% of the pixels serving as calibration types have been classified as belonging to Class 2. The confusion resulting from the heterogenous nature is evident in Blue Mesa (Figure 4-4), where Class 2 and Class 4 dominate. Particularly evident in Blue Mesa is the striping, a consequence of the MSS's sixth line banding. This striping contributes to the heterogeneity of training sites.

The six training sites on Blue Mesa were pooled with the three sites on Shadow Mountain Reservoir and one on Green Mountain Reservoir to form Class 4. It was expected that Blue Mesa would be wholly Class 4. The Class 2 spatial features of Blue Mesa are markedly linear, suggesting that they tie in with sixth line banding.

The five-class trophic maps of the nine lakes were examined visually on a training site by training site basis and, with three exceptions, excellent results were obtained for the 27 sites. Site 80803 on Green Mountain Reservoir is classified largely as being Class 3; it was originally pooled into Class 4. On Dillon Reservoir, site 80601 was pooled into Class 1; it is classified largely as Class 2. While pooled into Class 4, site 81302 on Shadow Mountain Reservoir is pictured on being largely Class 3. Overall, the resulting classifications of the nine reservoirs appear to be representative of their actual condition. Further work might lead to pooled classes which are spectrally more distinguishable and result in more accurate classification products.

3. Trophic Classification of Nine Colorado Lakes Based on a Nine-Class Multivariate Trophic Index

Figure 4-5, illustrates the classification results from nine Colorado lakes again using Landsat MSS data. The classification was based on the trophic ranking of 27 sampling sites derived from principal components ordination. Mean trophic indicator values were used to generate the PC1 index and 9 classes were chosen to represent the trophic scale. Six trophic indicators were again used in the principal components analysis. These were chlorophyll a, inverse Secchi disk, conductivity, total phosphorus, total organic nitrogen and algal assay yield. Table 4-30 depicts the classification accuracy.

There is a wide range in training site classification accuracy, with Class 1 having the greatest (80.0%) and Class 6 the lowest (36.7%). Again, the ideal value would be 100%. Each training class is not recognized as being homogeneous by the computer program. This suggests the need for merging some of the classes and/or deleting some of the sampling sites from the analysis.

As seen in Figure 4-5, the nine water bodies are not homogeneous. Again, the sixth line striping or banding is apparent, particularly in Blue Mesa Reservoir. The thematic photo maps suggest that Grand Lake, Cherry Creek Reservoir, and Milton Reservoir are relatively homogeneous. It is most unfortunate that the sixth line striping is so pronounced.

4. Chlorophyll a Classification of Nine Colorado Lakes

Figure 4-6 depicts the results of a classification based on chlorophyll a measurements taken at 27 sampling sites on nine Colorado lakes. The classification is again based on Landsat data. The field teams measured chlorophyll a in μg/liter; these measurements constitute one of several trophic indicators measured and recorded. Unlike the preceding two classifications, which are based on the combination of 6 different trophic indicators, this classification illustrates the distribution of an individual trophic indicator in each of nine lakes. The measurements for the 27 sampling sites were ranked on a numerical scale and then grouped into four classes to represent relative levels of chlorophyll a. Table 4-31 represents the classification accuracy.

As evidenced from the table, Class 1 with chlorophyll a values ranging from 2.1 to 4.1 μg/liter is the least homogeneous and Class 4 is the most homogeneous. A visual examination of the maps indicates that they compare favorably with the CHLA values found in Table 3-5. However, the Class 4 training sites have a very large CHLA range and perhaps should be divided to provide additional classes.

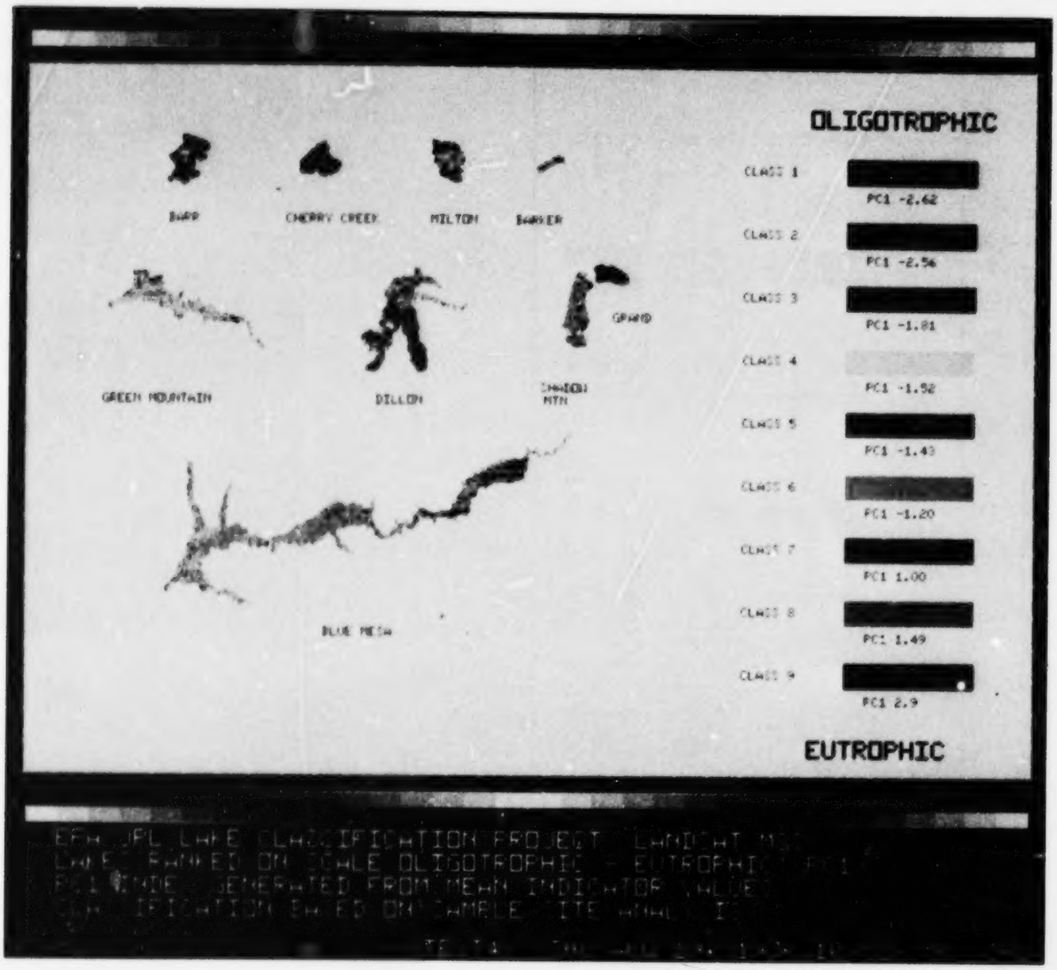
OLIGOTROPHIC
BARR
CHERRY CREEK
MILTON
BARKER
GREEN MOUNTAIN
DILLON
SHADOW MTN
GRAND
BLUE MESA
CLASS 1
PC1 -2.62
CLASS 2
PC1 -2.56
CLASS 3
PC1 -1.81
CLASS 4
PC1 -1.52
CLASS 5
PC1 -1.43
CLASS 6
PC1 -1.20
CLASS 7
PC1 1.00
CLASS 8
PC1 1.49
CLASS 9
PC1 2.9
EUTROPHIC
EPA JPL LAKE CLASSIFICATION PROJECT LANDSAT MSS
LAKES RANKED ON SCALE OLIGOTROPHIC - EUTROPHIC (PC1
PC1 INDEX GENERATED FROM MEAN INDICATOR VALUES
CLASSIFICATION BASED ON SAMPLE SITE ANALYSIS

Figure 4-5. Trophic Classification of Nine Colorado Lakes Based on a Nine Class Multivariate Trophic Index

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Table 4-30. Classification Analysis of Nine Colorado Lakes Based on a Nine-Class Multivariate Trophic Index

Lake	Class	0	1	2	3	4	5	6	7	8	9	Ambiguous
Grand	1	0.0	80.0	16.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Dillon	2	0.0	24.0	42.0	19.0	2.0	8.0	4.0	0.0	1.0	0.0	0.0
Barker	3	0.0	4.0	12.0	52.0	0.0	28.0	4.0	0.0	0.0	0.0	0.0
Green	4	0.0	0.0	0.0	1.5	72.7	1.5	1.5	0.0	15.1	7.5	0.0
Shadow Mountain	5	0.0	10.6	5.3	32.0	1.3	46.6	4.0	0.0	0.0	0.0	0.0
Blue Mesa	6	0.0	3.1	12.7	16.7	11.1	8.7	36.7	0.0	9.5	0.7	0.0
Cherry Creek	7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	73.3	16.0	10.6	0.0
Milton	8	0.0	0.0	2.0	2.0	4.0	0.0	2.0	8.0	78.0	4.0	0.0
Barr	9	0.0	0.0	0.0	0.0	2.0	0.0	0.0	26.0	4.0	68.0	0.0

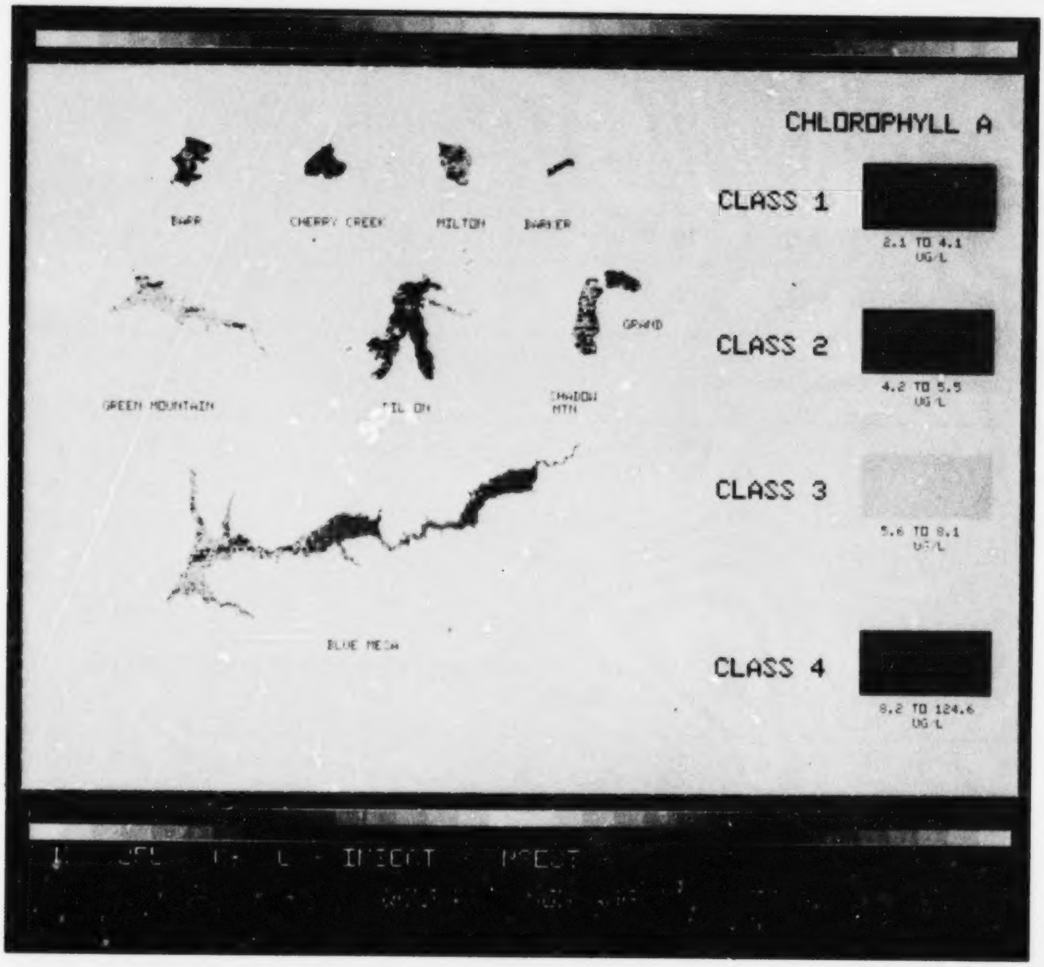
CHLOROPHYLL A
BARR
CHERRY CREEK
MILTON
BARKER
GREEN MOUNTAIN
DILLON
SHADOW MTN
GRAND
BLUE MESA
CLASS 1
2.1 TO 4.1 UG/L
CLASS 2
4.2 TO 5.5 UG/L
CLASS 3
5.6 TO 8.1 UG/L
CLASS 4
8.2 TO 124.6 UG/L

Figure 4-6. Chlorphyll a Classification of Nine Colorado Lakes

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Table 4-31. Analysis of Chlorophyll a Classification of Nine Colorado Lakes

	Percent Classified as					
Class	0*	1	2	3	4	Ambiguous
1	0.0	42.2	33.1	21.7	2.8	0.0
2	0.0	18.9	77.3	1.4	2.1	0.0
3	0.0	19.0	16.0	53.0	12.0	0.0
4	0.0	0.0	3.5	15.0	81.5	0.0

*Undefined classification

Table 4-32. Analysis of Inverse Secchi Depth Classification of Nine Colorado Lakes

	Percent Classified as					
Class	0*	1	2	3	4	Ambiguous
1	0.0	73.6	3.5	21.6	1.1	0.0
2	0.0	33.7	24.8	26.7	14.6	0.0
3	0.0	31.1	1.8	59.6	7.3	0.0
4	0.0	0.0	5.1	12.0	82.8	0.0

*Undefined classification

5. Inverse Secchi Depth Classification of Nine Colorado Lakes

The correlation of inverse Secchi disk transparency measurements with Landsat MSS data is illustrated in the thematic map in Figure 4-7. NES acquired Secchi disc measurements for 27 sampling sites on 9 lakes were numerically ranked and grouped into 4 classes to represent relative levels of eutrophication. As with the chlorophyll a content classification, this thematic map depicts an individual trophic indicator as opposed to a combination of trophic indicators (*i.e.*, multivariate trophic index such as the PC1). The class accuracies are found in Table 4-32. Class 2 is highly suspect because of its heterogeneity; only 24.8% of the pixels used to define it spectrally were identified as belonging to the class. Class 4 is clearly distinguishable from the others. The correlation between the ISEC maps and ISEC values in Table 3-5 is very good. It is very likely that even better correlations would result if additional effort were expended to further refine the classes.

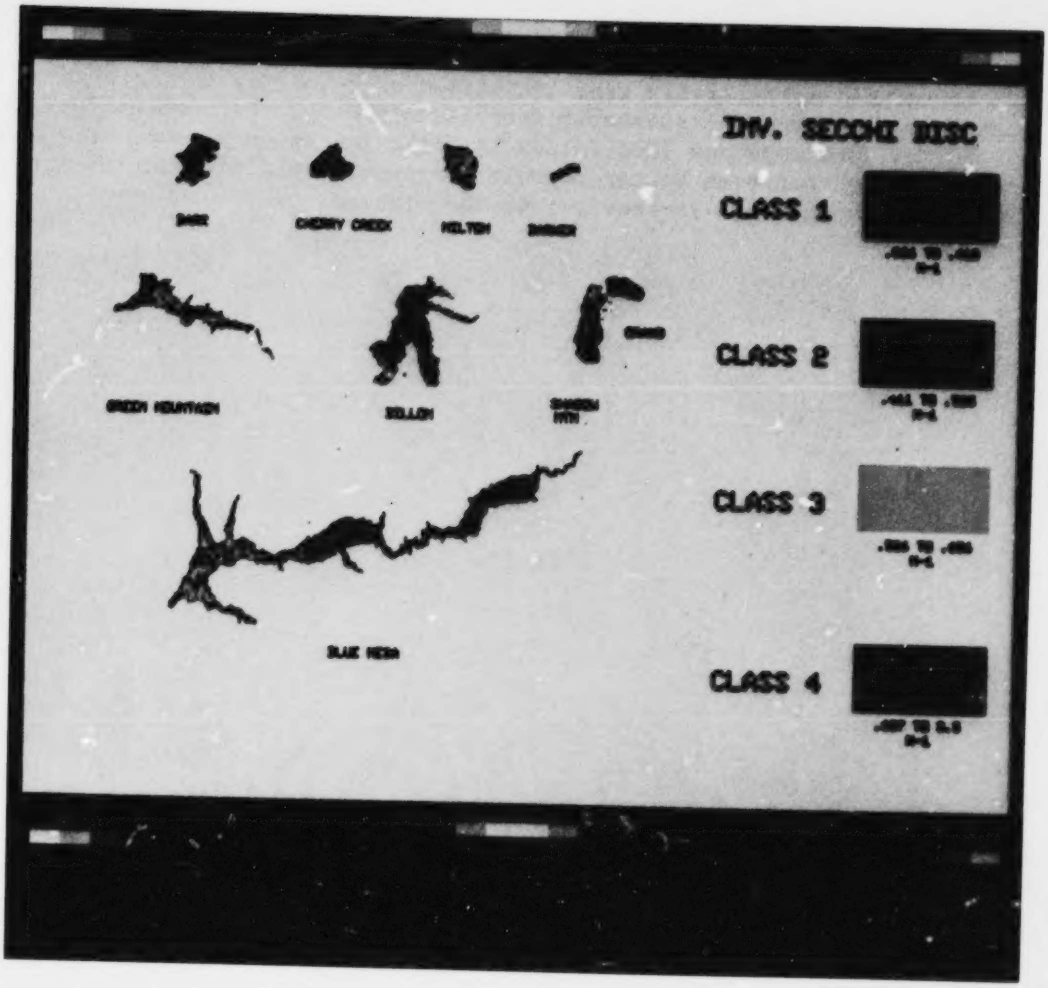
INV. SECCHI DISC
BARR
CHERRY CREEK
MILTON
GREEN MOUNTAIN
DILLON
SHADOW MTN
GRAND
BLUE MESA
CLASS 1
CLASS 2
CLASS 3
CLASS 4

Figure 4-7. Inverse Secchi Depth Classification Maps for Nine Colorado Lakes

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F. POINTS OF CONCERN

As evidenced from the previous discussion, the use of Landsat MSS and MMS data in lake classification work is not without its problems, some relating to the capabilities and limitations of the scanners, others to the characteristics of the scanner platforms, still others to environmental factors, such as the optical properties of water, the quantity and quality of the contact-sensed data, the dynamic nature of lacustrine bodies, and the very nature of the concept of trophic state.

The Landsat MSS was not designed specifically for water quality studies. It is a low resolution device both spatially and spectrally speaking. While the MMS has better resolution, both instruments have a rather limited dynamic range. The predictive capabilities of the scanners are effectively reduced by the disparity between the range of their data and those of the trophic indicators. The energy return from water is relatively small, particularly in the 600 nm to 1100 nm portion of the spectrum. Thus, the remotely sensed water quality information is contained in relatively weak signals over a very limited range.

The atmosphere can have a substantial effect on the character of the signal enroute to and coming from a water body. Atmospheric variability both over time and space adds variability to the remotely sensed data, thereby making the elucidation of relationships with the contact-sensed data much more difficult by increasing the element of uncertainty. The variability is remotely sensed data, in this case Landsat MSS data, is illustrated in Table 4-33. William Fork Reservoir and Granby Reservoir lie in the area of side overlaps; the DN values and pixel counts are those for two consecutive days. Ground truth is not available to separate the differences into an atmospheric component and a lacustrine component. Although these water bodies lie about two kilometers above sea level (and therefore above a substantial percentage of the atmosphere, this does not mean that the effects of atmosphere can be ignored. It was anticipated that the largest differences would be in the GRN band. This is contrary to the measured average differences of -0.08, -1.67, -2.21, and -2.09 for the GRN, RED, IR1, and IR2 bands, respectively. The atmosphere has a greater effect on short wavelengths than on long wavelengths. The above differences suggest that some other factor or factors (e.g., lacustrine dynamics, sensor characteristics) are also molding the character of the data generated from the electromagnetic energy.

Sun glint (i.e., specular reflection) is a major problem when collecting multispectral data from lakes using the aircraft-borne MMS. Of the 12 lakes flown over by the aircraft-borne scanner, usable data were only obtained from five; sun glint effectively marked the volume reflectance of the remaining lakes. Sun glint has not been demonstrated as being a major problem with the Landsat MSS.

The Landsat space observatory provides a stable platform from which to monitor the Earth. In contrast, aircraft platforms are inherently unstable, which leads to problems of geometric fidelity for which there are no easy or inexpensive solutions. The spacecraft is tied into a more or less fixed orbital path. This results in a set pattern of coverage which cannot take advantage of cloud-free days occurring other than the

Table 4-33. Changes in DN Values for Two Colorado Lakes Over Two Days

	Landsat Scene	Date	GRN	RED	IR1	IR2	Pixels
William Fork Reservoir	5126-16474	8-23-75	42.17 (3.49)	24.35 (4.70)	14.08 (6.29)	4.69 (5.94)	885
	5127-16532	8-24-75	42.36 (3.45)	26.52 (4.94)	16.52 (6.29)	7.11 (6.29)	875
			Δ-0.19	Δ-1.75	Δ-2.44	Δ-2.42	Δ7
Granby Reservoir	5126-16474	8-23-75	35.07 (3.80)	17.97 (4.48)	10.28 (5.71)	3.37 (5.33)	4166
	5127-16532	8-24-75	35.04 (2.93)	19.56 (3.70)	12.26 (4.72)	5.12 (4.78)	4362
			Δ0.03	Δ-1.59	Δ-1.98	Δ-1.75	Δ-196

fixed dates of flyover. On the other hand, aircraft can operate on a more flexible schedule, taking advantage of clear days.

Cloud cover is a major problem in the case of Landsat imagery. In this study, two of the five scenes of interest were not used because of excessive cloud cover. The problem becomes particularly acute when time series studies are attempted. Clouds add an element of chance to any lake program using satellite and aircraft-acquired remotely sensed data.

The success of efforts to develop predictive models and classification products through supervised approaches (e.g., Bayesian maximum likelihood classifier) is highly dependent upon the quantity and quality of contact-sensed data (i.e., calibration data). The contact-sensed data used in this study was collected with no thought of their being used in conjunction with remotely sensed data. The parameter values are highly skewed, necessitating the use of a transform function. This problem is frequently encountered in environmental data and must be addressed if regression is to be employed. Currently, there are no well recognized criteria to determine the number of sampling sites, parameters, and sampling techniques necessary to adequately assess the trophic condition of a lake. Trophic state itself is a multidimensional concept, and the parameters to be included in it are open to question.

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SECTION V

CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The following conclusions are drawn based on the elucidation of contact-sensed, Landsat MSS, and MMS data relationships for nine Colorado lakes.

(1) Both the LANDSAT MSS and the Bendix MMS can give estimates of lake surface area which are of practical value. Slightly better results are obtained with the MMS. More accurate estimates may be obtained using a multiband approach in place of the single band or channel approach reported here.

(2) Regression models can be developed from both MSS and MSS data for the prediction of specific trophic indicators. However, the model estimates do not have the precision and accuracy of those measurements acquired solely through contact sensing methods. Generally speaking, the MSS-related models give better estimates than the Landsat MSS-related models.

(3) The estimation of a numeric trophic state index is possible through the development of regression models using contact-sensed data and either MSS or MMS data. The MMS-related model provides better estimates than the Landsat model.

(4) The production of trophic index photomaps is feasible using contact-sensed data and either MSS or MMS data. Based on training site classification results, the MMS product is more accurate than the LANDSAT product.

It is suggested that the indications of better performance and results obtained using the MMS are due to its greater spectral and spatial resolution and less atmospheric interference, a consequence of the aircraft's relatively low altitude compared to that of Landsat.

B. RECOMMENDATIONS

As is evidenced by this report, the use of multispectral data in lake classification studies is not without its problems. To overcome or reduce the magnitude of the problems the following recommendations are made.

(1) An interactive image processing system (or subsystem) should be developed specifically for the classification of lakes. The system should be designed so the resource manager and lake scientist can employ it in a "hands on" mode; this should result in a more efficient use of equipment in terms of time and money and more accurate lake classification products. Such a system would have to contain a large

library of digital image preprocessing functions as well as statistical functions and supervised and unsupervised classificatory capabilities.

(2) The multivariate trophic indices used in this study are based on a relatively small sample set. Further consideration of the principal component approach to lake ordination should be directed toward a model (i.e., first principal component) developed from a large data base. The lakes included in the data base should not have turbidity problems attributable to suspended inorganic materials. High concentrations of inorganic suspended sediments result in light-limited conditions, changing the response curve relative to nutrient levels. It therefore follows that it is inappropriate to place all inland fresh water lakes on the same trophic scale. While five to six indicators were incorporated into the indices used in the investigation, the number and types may not be the most appropriate. Trophic index development is one area in need of further consideration. The principal component technique is intuitively appealing. However, other indices should also be examined.

(3) A multiband technique should be used to extract the water pixels from the terrestrial matrix.

(4) It is imperative that an effort be made to remove or reduce the magnitude of atmospheric effects. This might be accomplished by a "zeroing out" of the atmospheric component through use of deep, ultraoligotrophic water bodies, the assumption being that all of the energy return is from the atmosphere. More elegant techniques employing a combination of highly sophisticated equations and additional radiometric data might also be considered, but these are cumbersome and may not be cost-effective.

(5) An increase in the MSS's gain would be of value; it would increase the range of MSS data relating to water quality. However, it will result in sensor saturation for more land features.

(6) The sixth line striping so evident in water bodies is distracting cosmetically and also contributes "noise" which make MSS-ground truth relationships more difficult to decipher. Algorithm development should be undertaken to eliminate the problem or a MSS developed which is not plagued by it.

(7) This study was limited by circumstances to one point in time. The need exists to study the capabilities of the LANDSAT MSS for change detection. This would require the monitoring of a lake or group of lakes over a span of years.

(8) The spectral signatures identified for Colorado lakes under study should be extended to other water bodies in the same scene to determine if extrapolation techniques would be useful for classification and lake ranking.

GLOSSARY

AAY	algal assay yield (dry weight in mg/liter)
A-space	attribute space
CDC	Control Data Corporation
CH	channel of the modular multispectral scanner. More specifically, for example, CH4 is channel 4 (540 to 580 nm)
DCS	data collection system
DN	digital number level; the Landsat multispectral scanner data and modular multispectral scanner data were processed at 8 bits of precision resulting in 256 DN levels (0 to 255)
CCT's	computer compatible tapes
CERL	Corvallis Environmental Research Laboratory, Corvallis, Oregon
CHLA	chlorophyll a (μg/liter)
cm	centimeter
COND	conductivity (micromhos/centimeter)
EMSL-Las Vegas	Environmental Monitoring and Support Laboratory, Las Vegas, Nevada
EPA	U.S. Environmental Protection Agency
ERTS	Earth Resources Technology Satellite, the acronym and name originally applied to the NASA satellites designed to monitor the earth's resource; Landsat, an acronym for land satellite, is currently applied to the series
FOV	field of view
ha	hectare (10,000 square meters)
Hz	Hertz (i.e., cycles per second)
GRN	Landsat multispectral scanner green band with lower and upper limits of 500 and 600 nm, respectively
IBM	International Business Machines
IFOV	instantaneous field of view
IPL	Image Processing Laboratory, an operational unit at the Jet Propulsion Laboratory

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IR	infrared radiation
IR1	Landsat multispectral scanner near infrared one: band with lower and upper limits of 700 and 800 nm, respectively
IR2	Landsat multispectral scanner near infrared two: band with lower and upper limits of 800 and 1,100 nm, respectively
ISEC	inverse of Secchi depth (1/m)
JPL	Jet Propulsion Laboratory
Landsat	land satellite, the acronym currently applied to NASA's Earth Resources Technology Satellite (ERTS) series
LN	natural log-transformation
m	meter
mg	milligram
MMS	modular multispectral scanner
MMSPC1	first principal component resulting from principal component analysis of modular multispectral scanner data for 13 sites
MSS	multispectral scanner found in Landsat
NASA	National Aeronautics and Space Administration
NERC	National Environmental Research Center, a no longer functional unit of the U.S. EPA's Office of Research and Development
NES	National Eutrophication Survey
nm	nanometer (1×10^{-9}m)
NOAA	National Oceanic and Atmospheric Administration
PC1	multivariate trophic state index developed through principal component analysis of several (five or six) trophic indicators
PC1-11	multivariate trophic index developed through principal component analysis of six trophic indicators for 11 water bodies
PC1-13	multivariate trophic index developed through principal component analysis of six trophic indicators for 13 sampling sites in five Colorado lakes
PC1-27	multivariate trophic index developed through principal component analysis of six trophic indicators for 27 sampling sites in nine Colorado lakes

pixel	picture element, the basic unit of spatial resolution. The nominal pixel size for the Landsat multispectral scanner is 57 by 79 m; in this report data preprocessing has resulted in a Landsat pixel approximately 80 by 80 m. The modular multispectral scanner pixel is 15 by 15 m.
PL 92-500	Congressional act of 1972 entitled Federal Water Pollution Control Act Amendments
PMT	photomultiplier tube
R	multiple correlation coefficient
R^2	multiple correlation coefficient squared
RBV	return beam vidicon; each Landsat space observatory contains three RBVs
RED	Landsat multispectral scanner red band with lower and upper limits of 600 and 700 nm, respectively
r-matrix	product-moment correlation matrix
rps	revolutions per second
SEC	Secchi depth (m)
SIPS	Statistical Interactive Programming System, an interactive computer system at Oregon State University
sr	steradian
STORET	STOrage and RETrieval, the U.S. EPA's computer-based information system for water quality data
TON	total organic nitrogen (mg/liter)
TPHOS	Total phosphorus (mg/liter)
W	watt
USGS	U.S. Geological Survey
VERTSLOG	a VICAR application computer program which converts interleaved multispectral data into band sequential imagery; the program also performs radiometric and geometric corrections
V/H	velocity/height
mg	microgram
mm	micrometer

µsec	microsecond
1-D	one-dimensional space; characterized by a single attribute
^	estimated or predicted parameter value

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REFERENCES

Anderson, T.W. 1958. An Introduction to Multivariate Statistical Analysis. New York: John Wiley and Sons. 374 pp.

Atkins, W.R.G. and H.H. Poole. 1952. An experimental study of the scattering of light by natural waters. Proceedings of the Royal Society (London). Series B. 140:321-338.

Beeton, A.M. 1965. Eutrophication of the St. Lawrence Great Lakes. Limnology and Oceanography. 10(2):240-254.

Birge, E.A. and C. Juday, 1929. Transmission of solar radiation by the water of inland lakes. Transactions Wisconsin Academy Science Arts Letter. 24:509-580.

________________. 1930. A second report on solar radiation and inland lakes. Transactions Wisconsin Academy Science Arts Letters. 25:285-335.

________________. 1931. A third report on solar radiation and inland lakes. Transactions Wisconsin Academy Science Arts Letters. 26:383-425.

________________. 1932. A fourth report. Transactions Wisconsin Academy Science Arts Letters. 27:523-562.

Blackwell, R.J. and D.H.P. Boland. 1974. Computer analysis of lakes from ERTS imagery. In: Northwest '74 Pacific Regional Symposium on Computing the Resources Industry. Canadian Information Processing Society. 23-24 May 1974. Vancouver, B. C. pp. 147-157.

Blackwell, R.J. and D.H.P. Boland. 1975. The Trophic Classification of Lakes Using ERTS Multispectral Scanner Data. Proceedings American Society of Photogrammetry 41st Annual Meeting, March 9-14, 1975.

Boland, D.H.P. and R.J. Blackwell. 1975. The LANDSAT-1 multispectral scanner as a tool in the classification of inland lakes. Proceedings NASA Earth Resources Survey Symposium. First Comprehensive Symposium on the Practical Application of Earth Resources Survey Data. June 9-12, 1975. Shamrock Hilton. Houston, Texas. NASA TM X-58168. JSC-09930. I-A: 419-442.

Boland, D.H.P. 1976. Trophic Classification of Lakes Using LANDSAT-1 (ERTS-1) Multispectral Scanner Data. U.S. EPA Ecological Research Series Report. EPA-600/3-76-037. 263 pp.

Brezonik, P.L. and E.E. Shannon. 1971. Trophic State of Lakes in North Central Florida. Publication 13. Florida Water Resources Research Center. Gainesville: University of Florida. 102 pp.

Collins, J.R. 1925. Change in the infrared absorption spectrum of water with temperature. Physics Review. 26:771.

Curran, R.J. 1972. Ocean color determination through a scattering atmosphere. Applied Optics. 11(8):1857-1866.

Davis, F.J. 1941. Surface loss of solar and sky radiation by inland lakes. Transactions Wisconsin Academy Science Arts Letters. 33:83-93.

Dawson, L.H. and E.O. Hulburt. 1937. The scattering of light by water. Journal Optical Society America. 278:199-201.

Donaldson, J.R. 1969. The classification of lakes. Proceedings of the Eutrophication-Biostimulation Assessment Workshop. 19-21 June 1969. Held at Hotel Claremont, Berkeley, California. Sponsored by University of California (Berkeley) and Pacific Northwest Water Laboratory, U.S. Environmental Protection Agency. 171-185 pp.

Duntley, S.Q. 1963. Light in the sea. Journal Optical Society America. 53:214-233.

Edmondson, W.T. 1974. Review of: Environmental phosphorus handbook. Edited by E.J. Griffith, A. Beeton, J.M. Spencer, and D.T. Mitchell. New York: Wiley-Interscience. 1973. 718 pp. Limnology and Oceanography. 19(2):369-375.

Ewan, T. 1894. On the absorption spectra of dilute solutions. Proceedings Royal Society (London). 57:117-161.

Freden, S.C. 1973. Introduction: performance of sensors and systems. In: Earth Resources Technology Satellite-1 Symposium Proceedings. 29 September 1972. NASA (Goddard Space Flight Center). Compiled by W.A. Finch, Jr. pp. 1-6.

Gerd, W.V. 1957. An attempt at the biolimnological regionalization of the USSR. Transactions of the Sixth Conference on the Biology of Inland Waters. Edited by E.N. Pavlovskii. Original in Russian. Israel Program for Scientific Translations. Jerusalem: IPST Press. 1969. pp. 138-145.

Hansen, K. 1962. The dystrophic lake type. Hydrobiologia. 19(2)182-191.

Harding, S.T. 1942. Lakes. Hydrology. pp. 220-243. Edited by O.E. Meinzer. New York: McGraw-Hill. Dover edition by Dover Publications: New York. 712 pp.

Hasler, A.D. 1947. Eutrophication of lakes by domestic drainage. Ecology. 28:383-395.

Hasler, A.D. and B. Ingersoll, 1968. Dwindling lakes. Natural History. 77(9):8-19.

Hooper, F.F. 1969. Eutrophication indices and their relation to other indices of ecosystem change. In: Eutrophication: Causes, Consequences, Correctives. Proceedings of a Symposium. 11-15 June 1967. University of Wisconsin. Washington, D.C.: National Academy of Science. pp. 225-235.

Horowitz, H.M., R.F. Nalepka, P.D. Hyde, and J.P. Morgenstern. 1971. Estimating the proportions of objects within a single resolution element of a multispectral scanner. Proceedings 7th International Symposium on Remote Sensing. May 17-21, 1971. Ann Arbor, Michigan. 2:1307-1320.

Hotelling, H. 1933a. Analysis of a complex of statistical variables into principal components (I. Introduction). The Journal of Education Psychology. 24:417-441.

________________. 1933b. Analysis of a complex of statistical variables into principal components (II). The Journal of Education Psychology. 24:498-520.

________________. 1936. Simplified calculation of principal components. Psychometrika. 1(1):27-35.

Hulburt, E.O. 1945. Optics of distilled and natural water. Journal Optical Society America. 35(11):698-705.

Hulstrom, R.L. 1973. The cloud bright spot. Photogrammetric Engineering. 39(4):370-376.

Hutchinson, G.E. 1957. A Treatise on Limnology. Volume I. Geography, Physics, and Chemistry. New York: John Wiley. 1015 pp.

________________. 1967. A Treatise on Limnology. Volume II. Introduction to Lake Biology and the Limnoplankton. New York: John Wiley. 115 pp.

________________. 1973. Eutrophication. The scientific background of a contemporary practical problem. American Scientist. 61:269-279.

James, H.R. and E.A. Birge. 1938. A laboratory study of the absorption of light by lake waters. Transactions Wisconsin Academy Science Arts Letters. 31:1-154.

Jarnefelt, H. 1958. On the typology of northern lakes. Proceedings International Association Theoretical Applied Limnology (International Vereinigung fur Theoretische und Angewandte Limnologie). Volume XIII. Congress in Finland 1956. Edited by T.T. Macan. Stuttgart. pp. 228-235.

Jerlov, N.G. 1968. Optical Oceanography. Elsevier Oceanography Series. Volume 5. Amsterdam: Elsevier. 194 pp.

Juday, C. and E.A. Birge. 1933. The transparency, the color, and the specific conductance of the lake water of northwest Wisconsin. Transaction Wisconsin Academy Science Arts Letters. 28:205-259.

Larkin, P.A and T.G. Northcote. 1958. Factors in lake typology in British Columbia, Canada. Proceedings International Association Theoretical Applied Limnology (Verh. Internat. Ver. Limnol.). 13:252-262.

Lindeman, R.L. 1942. The trophic-dynamic aspect of ecology. Ecology. 23(4):399-418.

Lueschow, L.A., J.M. Helm, D.R. Winter, and G.W. Karl. 1970. Trophic nature of selected Wisconsin lakes. Wisconsin Academy Sciences Arts Letters. 58:237-264.

Margalef, R. 1958. "Trophic" typology versus biotic typology as exemplified in the regional limnology of northern Spain. Proceedings International Association Theoretical Applied Limnology. 13:339-349.

McCloy, K.R. 1977. The vector classifier. Proceedings 11th International Symposium of Remote Sensing of Environment. April 25-29, 1977. Ann Arbor, Michigan: Environmental Research Institute of Michigan. 1:535-543.

McCluney, W.R. 1976. Remote measurement of water color. Remote Sensing of Environment. 5:3-33.

Morrison, D.F. 1967. Multivariate Statistical Methods. New York: McGraw-Hill. 338 pp.

Moyle, J.B. 1945. Classification of lake waters upon the basis of hardness. Proceedings Minnesota Academy Science. 13:8-12.

__________________. 1946. Some indices of lake productivity. Transactions of the American Fisheries Society. 76:322-334.

National Aeronautics and Space Administration. 1972. NASA Earth Resources Technology Satellite Data Users Handbook. Goddard Space Flight Center. Document Number 71SD4249. Subject to revision.

Naumann, E. 1919. Nagra Synpunkte angaende planktons okologi. Med. sarskild hynsyn till fytoplanton. Svensk Botanisk Tidskrift. 13:129-158.

________________. 1931. Limnologische terminologie. Urban and Schwarzenberg. Berline: Wien. (pp. 153 and 413). 776 pp.

Nordberg, W. 1972. Written communication dated 9 November 1972. NASA Goddard Space Flight Center. Greenbelt, Maryland. 3 pp.

Pennak, R.W. 1958. Regional lake typology in northern Colorado, U.S.A. Proceedings International Association Theoretical Applied Limnology. 13:262-283.

Piech, K.R. and J.E. Walker. 1971. Aerial color analysis of water quality. Journal Survey Mapping Division. Proceedings American Society Civil Engineers. SU2(8507):185-197.

Raman, C.V. 1922. On the molecular scattering of light in water and the color of the sea. Proceedings Royal Society (London). Ser. A. 101:

Rawson, D.S. 1956. Algal indicator of trophic lake types. Limnology and Oceanography. 1(1):18-25.

_________________. 1960. A limnological comparison of twelve large lakes in northern Saskatchewan. Limnology and Oceanography. 5(2):195-211.

Rogers, R.H. and K. Peacock. 1973. A technique for correcting ERTS data for solar and atmospheric effects. Symnposium on Significant Results Obtained from the Earth Resources Technology Satellite-1. March 5-9, 1973. NASA (Goddard Space Flight Center). I-B:1115-1122.

Rogers, R.H., N.J. Shah, J.B. McKeon, and V.E. Smith. 1976. Computer mapping of water quality in Saginaw Bay with Landsat digital data. Proceedings of ACSM-ASP convention. February 22-28, 1976. Washington Hilton. NASA-CR-146057. NTIS E76-10124.

Round, F.E. 1958. Algal aspects of lake typology. Proceedings International Association Theoretical Applied Limnology. 13:306-310.

Ruttner, F. 1963. Fundamentals of Limnology. Third edition. Translated by D.G. Frey and F.E.J. Fry. Toronto: University of Toronto Press. 295 pp.

Sawyer, W.R. 1931. The spectral absorption of light by pure water and Bay of Fundy water. Contribution of Canadian Biology and Fisheries being studied from the Biolgoical Stations of Canada. Series D. Hydrographic. 7(8):73-89.

Shannon, E.E. 1970. Eutrophication-trophic state relationships in north and central Florida lakes. Doctoral dissertation. Gainesville: University of Florida. 257 pp.

Scherz, J.P., D.R. Graff, and W.C. Boyle. 1960. Photographic characteristics of water pollution. Photogrammetric Engineering. 35:38-43.

Sheldon, A. 1972. A quantitative approach to the classification of inland waters. In: Natural Environments. Studies in Theoretical and Applied Analysis. Edited by J.V. Krutilla. Baltimore: John Hopkins University Press. pp. 205-261.

Stewart, K.M. and G.A. Rohlich. 1967. Eutrophication--A review. Publication Number 35. California State Water Quality Control Board. Sacramento. 188 pp.

Taylor, W.D., L.R. Williams, S.C. Hern, and V.W. Lambou. (In preparation). Phytoplankton Water Quality Relationships in U.S. Lakes, Part VII: Comparison of Some New and Old Indices and Measurements of Trophic State. National Eutrophication Survey Working Paper Number 711.

U.S. Environmental Protection Agency. 1974. National Eutrophication Survey Methods for Lakes. Sampled in 1972. National Eutrophication Survey Working Paper Number 1. 40 pp.

U.S. Environmental Protection Agency. 1975. National Eutrophication Survey Methods 1973-1975. National Eutrophication Survey Working Paper Number 175. 91 pp.

Veatch, J.O. and C.R. Humphrys. 1966. Water and Water Use Terminology. Kaukauna, Wisconsin: Thomas Printing and Publishing. 375 pp.

Vollenweider, R.A. 1968. Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication. Technical report prepared for the Organization for Economic Cooperation and Development. Paris, France. 159 pp.

Weber, C.A. 1907. Aufbau and Vegetation der Moore Norddeutschlands. Beiblatter Botanische Jahrbucker rur Systematik. Pflanzengeschichte und Pflanzengeographie. 90:19-34. Supplement to Bot. Jahrb. 40.

Welch, P.S. 1952. Limnology. Second edition. New York: McGraw-Hill. 538 pp.

Wezernak, C.T. and F.C. Polcyn. 1972. Eutrophication assessment using remote sensing techniques. Proceedings of the Eighth International Symposium on Remote Sensing of Environment. 2-6 October 1972. Ann Arbor: University of Michigan. 1:541-551.

Wezernak, C.T., F.J. Tannis, and C.A. Bajza. 1975. Trophic Analysis of Inland Lakes. Ann Arbor: Environmental Research Institute of Michigan. 27 pp.

Whipple, G.C. 1898. Classifications of lakes according to temperature. America Naturalist. 32(373):25-33.

Winner, R.W. 1972. An evaluation of certain indices of eutrophy and maturity in lakes. Hydrobiologia. 40(2)223-245.

Work, E.A. and D.S. Gilmer. 1976. Utilization of satellite data for inventorying prairie ponds and lakes. Photogrammetric Engineering and Remote Sensing. 42(5):685-694.

Yarger, H.L. and J.R. McCauley. 1975. Quantitative water quality with Landsat and Skylab. Proceedings NASA Earth Resources Survey Symposium. First Comprehensive Symposium on the Practical Application of Earth Resources Survey Data. June 9-12, 1975. Shamrock Hilton. Houston, Texas. NASA TM X-58168. JSC-09930. I-A:347-370.

Zafar, A.R. 1959. Taxonomy of lakes. Hydrobiologia. 13(3):287-299

Zumberge, J.H. 1952. The Lakes of Minnesota: Their Origin and Classification. Minnesota Geological Survey Bulletin. Number 35. 99 pp.

APPENDIX A

PHYSICAL-CHEMICAL DATA FOR THE COLORADO LAKES STUDY

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STORET RETRIEVAL DATE 76/01/09

080101
39 57 56.0 105 29 00.0
BARKER RESERVOIR
08013 COLORADO

11EPALES 2111202
3 0085 FEET DEPTH

DATE FROM TO	TIME OF DAY	DEPTH FEET	00010 WATER TEMP CENT	00300 DO MG/L	00077 TRANSP SECCHI INCHES	00094 CNDUCTVY FIELD MICROMHO	00400 PH SU	00410 T ALK CACO3 MG/L	00610 NH3-N TOTAL MG/L	00625 TOT KJEL N MG/L	00630 NO2&NO3 N-TOTAL MG/L	00671 PHOS-DIS ORTHO MG/L P
75/05/07	09 00	0000	3.9	9.6	51	28	8.80	26	0.020K	0.400	0.060	0.012
	09 00	0005	3.7	9.4		38	8.80	26	0.020K	0.600	0.080	0.009
	09 00	0015	3.8	9.4		38	8.70	25	0.020	0.400	0.080	0.007
	09 00	0048	3.8	9.4		37	9.00	23	0.020	0.400	0.080	0.006
	09 00	0081	3.9	9.4		39	8.70	24	0.020	0.400	0.090	0.005
75/08/26	11 15	0000	15.6	7.6	96	29	8.35					
	11 15	0005	15.7	7.4		32	8.20					
	11 15	0018	15.6	7.6		29	8.00					
	11 15	0040	9.7	7.0		29	7.40					
	11 15	0080	7.4	6.4		29	7.00					
	11 15	0120	7.0	5.6		27	6.90					
75/10/10	10 15	0000	9.8	7.8	120	27	8.25					
	10 15	0005	9.8	7.4		28	8.10					
	10 15	0015	9.8	7.4		28	8.00					
	10 15	0035	9.7	7.6		27	8.50					
	10 15	0061	9.5	7.0		28	8.05					

STORET RETRIEVAL DATE 76/01/09

080101
39 57 56.0 105 29 00.0
BARKER RESERVOIR
08013 COLORADO

11EPALES 2111202
3 0085 FEET DEPTH

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DATE FROM TO	TIME OF DAY	DEPTH FEET	00665 PHOS-TOT MG/L P	32217 CHLRPHYL A UG/L	00031 INCDT LT REMNING PERCENT
75/05/07	09 00	0000	0.037	0.6	
	09 00	0005	0.037		
	09 00	0015	0.035		
	09 00	0048	0.037		
	09 00	0081	0.038		
75/08/26	11 15	0000		3.7	
75/10/10	10 15	0000		8.2	

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STORET RETRIEVAL DATE 76/01/09
                                                                      080102
                                                                     39 57 51.0 105 29 48.0
                                                                     BARKER RESERVOIR
                                                                     08001   COLORADO

                                                                     11EPALES               2111202
                                                                     3                     0021 FEET  DEPTH
                                  00010       00300       00077       00094       00400      00410      00610      00625      00630      00671
  DATE     TIME DEPTH  WATER        DO        TRANSP     CNDUCTVY      PH        T ALK      NH3-N     TOT KJEL   NO2&NO3    PHOS-DIS
  FROM      OF          TEMP                  SECCHI     FIELD                   CACO3      TOTAL        N       N-TOTAL     ORTHO
   TO      DAY  FEET    CENT       MG/L       INCHES     MICROMHO     SU          MG/L       MG/L       MG/L       MG/L      MG/L P

75/05/07 09 30 0000       3.7       10.8          48           39     8.50         24      0.030      0.400      0.090      0.006
         09 30 0005       3.7        9.6                       38     8.80         23      0.020      0.500      0.080      0.005
         09 30 0017       3.7        9.2                       38     8.40         24      0.020K     0.400      0.060      0.006
75/08/26 11 40 0000      15.4        7.0          75           32     9.10
         11 40 0005      15.4        7.6                              8.80
         11 40 0015      15.1        7.8                       32     8.40
         11 40 0026      13.1        7.0                       32     8.00
75/10/10 10 40 0000       9.6        7.2          96           28     8.50
         10 40 0005       9.6        7.4                       28     8.15
         10 40 0012       9.5        7.4                       28     7.90
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STORET RETRIEVAL DATE 76/01/09
                                                                      080102
                                                                     39 57 51.0 105 29 48.0
                                                                     BARKER RESERVOIR
                                                                     08001   COLORADO

                                                                     11EPALES               2111202
                                                                     3                     0021 FEET  DEPTH
                                  00665       32217       00031
  DATE     TIME DEPTH PHOS-TOT   CHLRPHYL    INCDT LT
  FROM      OF                      A        REMNING
   TO      DAY  FEET   MG/L P      UG/L      PERCENT

75/05/07 09 30 0000     0.034        9.0
         09 30 0005     0.040
         09 30 0017     0.035
75/08/26 11 40 0000                  3.7
75/10/10 10 40 0000                  6.8
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STORET RETRIEVAL DATE 76/01/09
                                                                    080201
                                                                   39 56 27.0 104 44 53.0
                                                                   BARR LAKE
                                                                   08001   COLORADO

                                                                   11EPALES             2111202
                                                                   3                    0030 FEET  DEPTH

                          00010     00300     00077     00094      00400     00410     00610     00625     00630     00671
 DATE     TIME DEPTH     WATER       DO      TRANSP    CNDUCTVY     PH       T ALK     NH3-N    TOT KJEL   NO2&NO3   PHOS-DIS
 FROM      OF             TEMP               SECCHI    FIELD                 CACO3     TOTAL       N       N-TOTAL    ORTHO
  TO      DAY  FEET       CENT      MG/L     INCHES    MICROMHO     SU        MG/L      MG/L      MG/L      MG/L      MG/L P

75/05/05 14 20 0000       12.7       8.4       120         752      8.15       250     6.460     6.500     1.510     1.170
         14 20 0005       12.8       8.4                   749      8.15       226     7.310     7.000     1.420     1.250
         14 20 0015       12.9       8.8                   749      8.20       232     6.510     6.900     1.470     1.680
         14 20 0026       12.0       7.2                   731      8.20       234     7.160     7.300     1.470     1.730
75/08/26 13 35 0000       24.4      16.6        12         608      9.40
         13 35 0005       22.2       7.6                   591      9.30
         13 35 0015       21.6       4.8                   591      9.00
75/10/10 11 30 0000       13.7       8.6        24         557      8.80
         11 30 0005                  8.0                   554      8.90
         11 30 0015       13.3       8.2                   551      9.00
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STORET RETRIEVAL DATE 76/01/09
                                                                    080201
                                                                   39 56 27.0 104 44 53.0
                                                                   BARR LAKE
                                                                   08001   COLORADO

                                                                   11EPALES             2111202
                                                                   3                    0030 FEET  DEPTH

                          00665     32217     00031
 DATE     TIME DEPTH   PHOS-TOT   CHLRPHYL   INCDT LT
 FROM      OF                        A       REMNING
  TO      DAY  FEET      MG/L P     UG/L     PERCENT

75/05/05 14 20 0000       1.780       4.3
         14 20 0005       1.750
         14 20 0015       1.740
         14 20 0026       1.770
75/08/26 13 35 0000                  74.4
75/10/10 11 30 0000                  32.5
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STORET RETRIEVAL DATE 76/01/09
                                                                    080202
                                                                   39 56 27.0 104 45 48.0
                                                                   BARR LAKE
                                                                   08123   COLORADO

                                                                   11EPALES              2111202
                                                                   3                    0016 FEET  DEPTH
                               00010      00300      00077      00094      00400     00410     00610     00625     00630     00671
 DATE     TIME DEPTH   WATER      DO       TRANSP   CNDUCTVY     PH       T ALK     NH3-N   TOT KJEL   NO2&NO3  PHOS-DIS
 FROM      OF          TEMP                SECCHI   FIELD                 CACO3     TOTAL       N      N-TOTAL   ORTHO
  TO      DAY  FEET    CENT      MG/L      INCHES   MICROMHO     SU        MG/L      MG/L      MG/L      MG/L     MG/L P

75/05/05 14 55 0000     11.7       9.2        72        723     8.40        234     6.180     8.300     1.550     1.660
         14 55 0005     11.8       9.0                  724     8.35        228     6.590     7.900     1.450     1.490
         14 55 0012     11.7       9.2                  723     8.35        186     1.390     7.700     2.140     1.640
75/08/26 13 40 0000     22.5       9.6        24        598     9.25
         13 40 0005     22.0       7.2                  591     9.15
         13 40 0010     21.5       7.4                  590     9.10
75/10/10 11 15 0000     14.0       9.0        40        561     9.00
         11 15 0005     13.5       8.0                  556     9.00
         11 15 0016     13.1       7.2                  560     9.00
```

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STORET RETRIEVAL DATE 76/01/09
                                                                    080202
                                                                   39 56 27.0 104 45 48.0
                                                                   BARR LAKE
                                                                   08123   COLORADO

                                                                   11EPALES              2111202
                                                                   3                    0016 FEET  DEPTH
                          00665      32217      00031
 DATE     TIME DEPTH   PHOS-TOT   CHLRPHYL   INCDT LT
 FROM      OF                        A       REMNING
  TO      DAY  FEET    MG/L P       UG/L     PERCENT

75/05/05 14 55 0000      1.750       12.8
         14 55 0005      1.810
         14 55 0012      1.730
75/08/26 13 40 0000                  29.0
75/10/10 11 15 0000                  19.6
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STORET RETRIEVAL DATE 76/01/09
                                                                      080401
                                                                     39 38 58.0 104 51 13.0
                                                                     CHERRY CREEK LAKE
                                                                     08005   COLORADO

                                                                     11EPALES            2111202
                                                                     3                  0010 FEET  DEPTH

                       00010      00300      00077      00094      00400      00410      00610      00625      00630      00671
 DATE   TIME DEPTH    WATER        DO       TRANSP    CNDUCTVY      PH       T ALK     NH3-N    TOT KJEL   NO2&NO3   PHOS-DIS
 FROM    OF            TEMP                 SECCHI    FIELD                  CACO3     TOTAL        N      N-TOTAL     ORTHO
  TO    DAY  FEET      CENT       MG/L      INCHES    MICROMHO      SU        MG/L      MG/L       MG/L      MG/L      MG/L P

75/05/07 10 45 0000      9.7        8.2         33        377       8.50       175     0.030      0.900     0.030      0.009
         10 45 0006      9.7        8.0                   378       8.50
75/08/22 14 25 0000     22.9        7.2         36        574       8.00
         14 25 0005     23.1        6.4                   770       8.30
         14 25 0018     22.6        6.0                   567       8.35
75/10/09 10 55 0000     13.9        8.0         24        422       8.15
         10 55 0005     13.5        8.0                   422       8.20
         10 55 0015     13.1        7.6                   418       8.25
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STORET RETRIEVAL DATE 76/01/09
                                                                      080401
                                                                     39 38 58.0 104 51 13.0
                                                                     CHERRY CREEK LAKE
                                                                     08005   COLORADO

                                                                     11EPALES            2111202
                                                                     3                  0010 FEET  DEPTH

                       00665      32217      00031
 DATE   TIME DEPTH  PHOS-TOT   CHLRPHYL    INCDT LT
 FROM    OF                        A       REMNING
  TO    DAY  FEET    MG/L P      UG/L      PERCENT

75/05/07 10 45 0000    0.057       12.8
75/08/22 14 25 0000                 9.8
75/10/09 10 55 0000                14.2
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STORET RETRIEVAL DATE 76/01/09
                                                                   080402
                                                                  39 38 18.0 104 51 57.0
                                                                  CHERRY CREEK LAKE
                                                                  08005    COLORADO

                                                                  11EPALES               2111202
                                                                  3                     0013 FEET  DEPTH
                                00010       00300       00077      00094        00400      00410      00610      00625      00630      00671
 DATE    TIME DEPTH  WATER       DO        TRANSP     CNDUCTVY      PH        T ALK      NH3-N     TOT KJEL   NO2&NO3    PHOS-DIS
 FROM     OF          TEMP                  SECCHI     FIELD                   CACO3      TOTAL        N       N-TOTAL     ORTHO
  TO     DAY  FEET    CENT        MG/L      INCHES     MICROMHO     SU         MG/L       MG/L       MG/L       MG/L      MG/L P

75/05/07 11 05 0000    10.2         8.2         37         380
         11 05 0009     9.9         7.6                    378      8.50        175      0.040      0.800     0.020K     0.009
75/08/22 14 00 0000    24.3         7.6         26         607      8.50
         14 00 0005    23.4         5.0                    564      8.50
75/10/09 11 15 0000    13.9         8.0         24         425      8.20
         11 15 0005    13.9         7.6                    425      8.25
         11 15 0010    13.5         7.4                    422      8.25


STORET RETRIEVAL DATE 76/01/09
                                                                   080402
                                                                  39 38 18.0 104 51 57.0
                                                                  CHERRY CREEK LAKE
                                                                  08005    COLORADO

                                                                  11EPALES               2111202
                                                                  3                     0013 FEET  DEPTH
                             00665      32217      00031
 DATE    TIME DEPTH PHOS-TOT   CHLRPHYL   INCDT LT
 FROM     OF                       A       REMNING
  TO     DAY  FEET   MG/L P      UG/L      PERCENT

75/05/07 11 05 0000              13.2
         11 05 0009   0.056
75/08/22 14 00 0000             124.6
75/10/09 11 15 0000               9.8
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STORET RETRIEVAL DATE 76/01/09
                                                                                080403
                                                                               39 38 12.0 104 50 55.0
                                                                               CHERRY CREEK LAKE
                                                                               08089   COLORADO

                                                                               11EPALES             2111202
                                                                               3                  0019 FEET  DEPTH
                               00010      00300      00077      00094       00400      00410      00610      00625      00630      00671
 DATE      TIME DEPTH  WATER       DO        TRANSP     CNDUCTVY      PH       T ALK      NH3-N    TOT KJEL   NO2&NO3   PHOS-DIS
 FROM       OF          TEMP                 SECCHI     FIELD                  CACO3      TOTAL       N       N-TOTAL    ORTHO
  TO       DAY  FEET    CENT       MG/L      INCHES     MICROMHO     SU        MG/L       MG/L       MG/L       MG/L     MG/L P

75/05/07  11 30 0000      10.3       8.0         36         382      8.70        176      0.030      0.800     0.020K     0.009
          11 30 0005      10.2       8.0                    381      8.50        176      0.040      0.800     0.020K     0.010
          11 30 0015      10.0       8.0                    382      8.50        176      0.030      0.900     0.020K     0.011
75/08/22  14 30 0000      23.4       7.2         24         579      8.50
          14 30 0005      23.5       7.2                    570      8.50
          14 30 0014      22.6       5.8                    565      8.40
75/10/09  10 40 0000      13.7       7.6         36         426      8.10
          10 40 0005      13.6       7.4                    421      8.25
          10 40 0010      13.4       7.6                    418      8.30


STORET RETRIEVAL DATE 76/01/09
                                                                                080403
                                                                               39 38 12.0 104 50 55.0
                                                                               CHERRY CREEK LAKE
                                                                               08089   COLORADO

                                                                               11EPALES             2111202
                                                                               3                  0019 FEET  DEPTH
                               00665      32217      00031
 DATE      TIME DEPTH PHOS-TOT   CHLRPHYL   INCDT LT
 FROM       OF                      A       REMNING
  TO       DAY  FEET    MG/L P     UG/L     PERCENT

75/05/07  11 30 0000     0.051       2.3
          11 30 0005     0.070
          11 30 0015     0.065
75/08/22  14 30 0000                11.6
75/10/09  10 40 0000                11.6
```

ORIG
OF POOR QUALITY

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STORET RETRIEVAL DATE 76/01/09
                                                               080601
                                                              39 36 30.0 106 01 22.0
                                                              DILLON RESERVOIR
                                                              08117   COLORADO

                                                              11EPALES              2111202
                                                              3                    0075 FEET  DEPTH

                             00010     00300     00077     00094      00400     00410     00610     00625     00630     00671
 DATE     TIME DEPTH  WATER      DO     TRANSP    CNDUCTVY     PH      T ALK    NH3-N    TOT KJEL  NO2&NO3   PHOS-DIS
 FROM      OF         TEMP              SECCHI    FIELD                 CACO3    TOTAL       N      N-TOTAL    ORTHO
  TO      DAY  FEET   CENT      MG/L    INCHES    MICROMHO     SU       MG/L     MG/L      MG/L     MG/L      MG/L P

75/08/25 09 20 0000    12.6      7.4      180         97      7.60
         09 20 0005    12.4      7.2                  94      7.70
         09 20 0030    10.1      7.0                  82      7.40
         09 20 0045     7.5      6.8                  85      7.20
         09 20 0071     6.1      6.6                  87      7.20
75/10/09 14 50 0000    11.2      7.8      252          1      7.40
         14 50 0005    11.1      8.0                          7.60
         14 50 0023    11.0      8.2                   1      7.60
         14 50 0050    10.4      7.6                   1      7.50
         14 50 0075     9.5      6.6                   1      7.40


STORET RETRIEVAL DATE 76/01/09
                                                               080601
                                                              39 36 30.0 106 01 22.0
                                                              DILLON RESERVOIR
                                                              08117   COLORADO

                                                              11EPALES              2111202
                                                              3                    0075 FEET  DEPTH

                             00665     32217     00031
 DATE     TIME DEPTH  PHOS-TOT  CHLRPHYL  INCDT LT
 FROM      OF                      A      REMNING
  TO      DAY  FEET    MG/L P     UG/L    PERCENT

75/08/25 09 20 0000                 2.2
75/10/09 14 50 0000                 3.7
```

STORET RETRIEVAL DATE 76/01/09

080602
39 35 00.0 106 03 00.0
DILLON RESERVOIR
08117 COLORADO

11EPALES
3

2111202
0047 FEET DEPTH

DATE FROM TO	TIME OF DAY	DEPTH FEET	00010 WATER TEMP CENT	00300 DO MG/L	00077 TRANSP SECCHI INCHES	00094 CNDUCTVY FIELD MICROMHO	00400 PH SU	00410 T ALK CACO3 MG/L	00610 NH3-N TOTAL MG/L	00625 TOT KJEL N MG/L	00630 NO2&NO3 N-TOTAL MG/L	00671 PHOS-DIS ORTHO MG/L P
75/08/25	09 45	0000	13.4	7.6	204	97	7.55					
	09 45	0005	13.2	7.5		97	7.75					
	09 45	0020	17.9	7.6		95	7.90					
	09 45	0038	8.0	6.0		87	7.55					
	09 45	0043	7.7	6.0		87	7.35					
75/10/09	14 00	0000	11.2	8.2	206	97	7.60					
	14 00	0005	11.2	8.0		94	7.75					
	14 00	0023	10.6	8.0		94	7.80					
	14 00	0044	10.3	8.0		94	7.80					

STORET RETRIEVAL DATE 76/01/09

080602
39 35 00.0 106 03 00.0
DILLON RESERVOIR
08117 COLORADO

11EPALES
3

2111202
0047 FEET DEPTH

DATE FROM TO	TIME OF DAY	DEPTH FEET	00665 PHOS-TOT MG/L P	32217 CHLRPHYL A UG/L	00031 INCDT LT REMNING PERCENT
75/08/25	09 45	0000		2.5	
75/10/09	14 00	0000		4.9	

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STORET RETRIEVAL DATE 76/01/09
                                                                   080603
                                                                  39 35 00.0 106 04 07.0
                                                                  DILLON RESERVOIR
                                                                  08117   COLORADO

                                                                  11EPALES              2111202
                                                                  3                    0044 FEET  DEPTH
                                 00010      00300      00077      00094      00400     00410      00610      00625      00630      00671
  DATE   TIME DEPTH  WATER        DO       TRANSP    CNDUCTVY      PH       T ALK      NH3-N    TOT KJEL   NO2&NO3   PHOS-DIS
  FROM    OF          TEMP                 SECCHI    FIELD                  CACO3      TOTAL       N       N-TOTAL    ORTHO
   TO    DAY  FEET    CENT       MG/L      INCHES    MICROMHO      SU        MG/L       MG/L      MG/L       MG/L     MG/L P

75/08/25 10 15 0000    13.0        7.2        600         96      8.35
         10 15 0005    13.0        7.2                    96      8.15
         10 15 0020    12.4        7.0                    94      7.90
         10 15 0040     8.7        6.2                    89      7.60
75/10/09 14 30 0000    11.0        7.8        252          1      7.80
         14 30 0005    10.8        7.8                     1      7.80
         14 30 0023    10.8        7.8                     1      7.70
         14 30 0055    10.8        8.0                     1      7.70
```

```
STORET RETRIEVAL DATE 76/01/09
                                                                   080603
                                                                  39 35 00.0 106 04 07.0
                                                                  DILLON RESERVOIR
                                                                  08117   COLORADO

                                                                  11EPALES              2111202
                                                                  3                    0044 FEET  DEPTH
                          00665      32217      00031
  DATE   TIME DEPTH PHOS-TOT   CHLRPHYL   INCDT LT
  FROM    OF                      A        REMNING
   TO    DAY  FEET   MG/L P      UG/L      PERCENT

75/08/25 10 15 0000                 2.1
75/10/09 14 30 0000                 2.8
```

```
STORET RETRIEVAL DATE 76/01/09
                                                                    080604
                                                                   39 36 22.0 106 03 45.0
                                                                   DILLON RESERVOIR
                                                                   16043   COLORACO

                                                                   11EPALES            2111202
                                                                   3                   0109 FEET  DEPTH

                          00010     00300     00077     00094     00400     00410     00610     00625     00630     00671
  DATE    TIME DEPTH   WATER        DO      TRANSP   CNDUCTVY      PH      T ALK     NH3-N    TOT KJEL  NO2&NO3  PHOS-DIS
  FROM     OF            TEMP                SECCHI   FIELD                  CACO3     TOTAL       N      N-TOTAL    ORTHO
   TO     DAY  FEET      CENT       MG/L    INCHES   MICROMHO     SU        MG/L      MG/L      MG/L      MG/L     MG/L P

75/08/25 10 45 0000      13.0        7.6      252         96      7.80
         10 45 0005      13.1        7.3                  93      7.70
         10 45 0037      10.4        6.6                  84      7.40
         10 45 0060       6.4        6.8                  82      7.20
         10 45 0105       4.2        6.9                  88      7.00
75/10/09 13 15 0000      11.0        7.8      600          1      7.80
         13 15 0005      11.0        7.6                   1      7.85
         13 15 0023      10.8        8.0                   1      7.85
         13 15 0045      10.8        7.8                   1      7.80
         13 15 0075       9.0        5.8                   1      7.60
         13 15 0120       7.1        6.2                   1      7.50
         13 15 0165       6.5        6.6                   1      7.60


STORET RETRIEVAL DATE 76/01/09
                                                                    080604
                                                                   39 36 22.0 106 03 45.0
                                                                   DILLON RESERVOIR
                                                                   16043   COLORADO

                                                                   11EPALES            2111202
                                                                   3                   0109 FEET  DEPTH

                          00665     32217     00031
  DATE    TIME DEPTH PHOS-TOT  CHLRPHYL  INCDT LT
  FROM     OF                        A       REMNING
   TO     DAY  FEET    MG/L P      UG/L    PERCENT

75/08/25 10 45 0000                 2.4
75/10/09 13 15 0000                 4.6
```

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STORET RETRIEVAL DATE 76/01/09
                                                                            080801
                                                                           39 52 34.0 106 18 57.0
                                                                           GREEN MOUNTAIN RESERVOIR
                                                                           08117   COLORADO

                                                                           11EPALES             2111202
                                                                           3                    0070 FEET  DEPTH

                             00010     00300     00077      00094     00400    00410    00610    00625    00630     00671
 DATE    TIME DEPTH WATER      DO     TRANSP   CNDUCTVY     PH      T ALK    NH3-N   TOT KJEL  NO2&NO3  PHOS-DIS
 FROM     OF         TEMP              SECCHI   FIELD                CACO3    TOTAL      N     N-TOTAL    ORTHO
  TO     DAY  FEET   CENT     MG/L    INCHES   MICROMHO     SU       MG/L     MG/L     MG/L     MG/L     MG/L P

75/08/25 13 30 0000   13.5      7.2       96        114     7.60
         13 30 0005   13.8      7.2                 110     8.10
         13 30 0022   13.5      7.0                 109     7.90
         13 30 0040   12.6      6.8                 108     7.85
         13 30 0066   11.0      5.9                 103     7.60
75/10/09 16 50 0000   13.0      7.2      156        101     7.75
         16 50 0005   12.8      7.2                 106     7.80
         16 50 0018   12.5      7.2                   1     7.80
         16 50 0045   12.5      7.2                   1     7.80
         16 50 0090   12.4      7.4                   1     7.75
         16 50 0129   12.5      7.0                   1     7.70


STORET RETRIEVAL DATE 76/01/09
                                                                            080801
                                                                           39 52 34.0 106 18 57.0
                                                                           GREEN MOUNTAIN RESERVOIR
                                                                           08117   COLORADO

                                                                           11EPALES             2111202
                                                                           3                    0070 FEET  DEPTH

                            00665     32217     00031
 DATE    TIME DEPTH PHOS-TOT  CHLRPHYL  INCDT LT
 FROM     OF                      A      REMNING
  TO     DAY  FEET   MG/L P     UG/L    PERCENT

75/08/25 13 30 0000               7.9
75/10/09 16 50 0000               3.1
```

```
STORET RETRIEVAL DATE 76/01/09
                                                                080802
                                                                39 52 15.0 106 16 57.0
                                                                GREEN MOUNTAIN RESERVOIR
                                                                08117   COLORADO

                                                                11EPALES             2111202
                                                                3                    0095 FEET  DEPTH

                       00010     00300     00077     00094      00400     00410     00610     00625     00630     00671
 DATE   TIME DEPTH    WATER       DO      TRANSP   CNDUCTVY      PH       T ALK     NH3-N   TOT KJEL   NO2&NO3   PHOS-DIS
 FROM    OF            TEMP               SECCHI   FIELD                  CACO3     TOTAL       N      N-TOTAL    ORTHO
  TO    DAY  FEET      CENT      MG/L     INCHES   MICROMHO      SU        MG/L      MG/L      MG/L      MG/L     MG/L P

75/08/25 14 00 0000      14.8       7.4        80        107      8.20
         14 00 0005      14.7       7.5                  107      8.20
         14 00 0021      14.3       7.0                  105      8.10
         14 00 0055      12.2       6.6                  102      7.75
         14 00 0091      10.9       6.7                  104      7.50
75/10/09 16 30 0000      12.9       7.4       138        108      7.80
         16 30 0005      12.9       7.8                  108      7.90
         16 30 0016      12.8       7.8                  107      7.90
         16 30 0040      12.7       7.4                  104      7.90
         16 30 0062      12.5       7.4                  107      7.90
```

```
STORET RETRIEVAL DATE 76/01/09
                                                                080802
                                                                39 52 15.0 106 16 57.0
                                                                GREEN MOUNTAIN RESERVOIR
                                                                08117   COLORADO

                                                                11EPALES             2111202
                                                                3                    0095 FEET  DEPTH

                       00665     32217     00031
 DATE   TIME DEPTH  PHOS-TOT   CHLRPHYL   INCDT LT
 FROM    OF                        A      REMNING
  TO    DAY  FEET     MG/L P      UG/L    PERCENT

75/08/25 14 00 0000                  7.1
75/10/09 16 30 0000                  4.0
```

```
STORET RETRIEVAL DATE 76/01/09
                                                                  080803
                                                                 39 50 07.0 106 14 30.0
                                                                 GREEN MOUNTAIN RESERVOIR
                                                                 08117   COLORADO

                                                                 11EPALES             2111202
                                                                 3                  0027 FEET  DEPTH
                      00010     00300     00077     00094     00400     00410     00610     00625     00630     00671
 DATE    TIME DEPTH  WATER       DO      TRANSP   CNDUCTVY     PH       T ALK    NH3-N    TOT KJEL  NO2&NO3   PHOS-DIS
 FROM     OF          TEMP               SECCHI   FIELD                 CACO3    TOTAL       N      N-TOTAL    ORTHO
  TO     DAY  FEET    CENT     MG/L      INCHES   MICROMHO     SU        MG/L      MG/L      MG/L     MG/L     MG/L P

75/08/25 14 30 0000    14.6        7.2        75       109       7.70
         14 30 0005    14.7        7.3                 108       8.05
         14 30 0018    14.0        7.2                 108       8.00
         14 30 0024    13.2        7.2                 109       8.10
75/10/09 16 00 0000    12.7        7.8       108       109       7.55
         16 00 0005    12.8        8.0                   1       8.00
         16 00 0015    10.0        8.2                   1       8.00
         16 00 0023     6.8        9.6                   1       8.00


STORET RETRIEVAL DATE 76/01/09
                                                                  080803
                                                                 39 50 07.0 106 14 30.0
                                                                 GREEN MOUNTAIN RESERVOIR
                                                                 08117   COLORADO

                                                                 11EPALES             2111202
                                                                 3                  0027 FEET  DEPTH

                     00665     32217     00031
 DATE    TIME DEPTH PHOS-TOT  CHLRPHYL  INCDT LT
 FROM     OF                     A      REMNING
  TO     DAY  FEET    MG/L P   UG/L     PERCENT

75/08/25 14 30 0000                9.8
75/10/09 16 00 0000                3.1
```

```
STORET RETRIEVAL DATE 76/01/09
                                                                          081001
                                                                         38 13 12.0 103 40 13.0
                                                                         LAKE MEREDITH
                                                                         08025   COLORADO

                                                                         11EPALES              2111202
                                                                         3                    0005 FEET  DEPTH

                          00010      00300      00077      00094      00400      00410      00610      00625      00630      00671
  DATE    TIME DEPTH     WATER        DO       TRANSP     CNDUCTVY     PH        T ALK      NH3-N     TOT KJEL   NO2&NO3    PHOS-DIS
  FROM     OF             TEMP                 SECCHI     FIELD                  CACO3      TOTAL        N       N-TOTAL     ORTHO
   TO     DAY  FEET       CENT       MG/L      INCHES     MICROMHO     SU         MG/L       MG/L       MG/L       MG/L      MG/L P

75/05/06 11 00 0000        12.8        7.6         11        3949      8.50        108      0.320      3.100      0.060      0.099
75/08/22 11 30 0000        23.8        5.4         10        7096      9.00
75/10/07 14 50 0000        17.7        8.0         10        7000      9.10
```

```
STORET RETRIEVAL DATE 76/01/09
                                                                          081001
                                                                         38 13 12.0 103 40 13.0
                                                                         LAKE MEREDITH
                                                                         08025   COLORADO

                                                                         11EPALES              2111202
                                                                         3                    0005 FEET  DEPTH

                          00665      32217      00031
  DATE    TIME DEPTH    PHOS-TOT   CHLRPHYL   INCDT LT
  FROM     OF                         A       REMNING
   TO     DAY  FEET     MG/L P       UG/L     PERCENT

75/05/06 11 00 0000      0.326        46.2
75/08/22 11 30 0000                  151.3
75/10/07 14 50 0000                  278.2
```

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STORET RETRIEVAL DATE 76/01/09
                                                                      081002
                                                                     38 12 12.0 103 41 14.0
                                                                     LAKE MEREDITH
                                                                     08025   COLORADO

                                                                     11EPALES              2111202
                                                                     3                     0006 FEET  DEPTH

                          00010      00300      00077      00094      00400      00410      00610      00625      00630      00671
 DATE   TIME DEPTH    WATER        DO       TRANSP   CNDUCTVY       PH       T ALK      NH3-N    TOT KJEL   NO2&NO3   PHOS-DIS
 FROM    OF            TEMP                 SECCHI   FIELD                   CACO3      TOTAL        N      N-TOTAL     ORTHO
  TO    DAY  FEET      CENT       MG/L      INCHES   MICROMHO       SU        MG/L       MG/L       MG/L      MG/L      MG/L P

75/05/06 11 40 0000      13.6        8.0          11       3987      8.65        106      0.200      3.400      0.040      0.072
75/08/22 11 15 0000      23.6        4.6          11       7094      8.90
75/10/07 15 10 0000      17.9        7.2          10       7055      9.10
```

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STORET RETRIEVAL DATE 76/01/09
                                                                      081002
                                                                     38 12 12.0 103 41 14.0
                                                                     LAKE MEREDITH
                                                                     08025   COLORADO

                                                                     11EPALES              2111202
                                                                     3                     0006 FEET  DEPTH

                         00665      32217      00031
 DATE   TIME DEPTH PHOS-TOT   CHLRPHYL   INCDT LT
 FROM    OF                       A      REMNING
  TO    DAY  FEET    MG/L P     UG/L     PERCENT

75/05/06 11 40 0000    0.338       32.8
75/08/22 11 15 0000               151.3
75/10/07 15 10 0000               271.3
```

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STORET RETRIEVAL DATE 76/01/09
                                                                    081003
                                                                    38 10 42.0 103 43 31.0
                                                                    LAKE MEREDITH
                                                                    35061   COLORADO

                                                                    11EPALES            2111202
                                                                    3                   0004 FEET  DEPTH

                             00010     00300     00077     00094      00400     00410     00610     00625     00630     00671
 DATE    TIME DEPTH WATER      DO      TRANSP    CNDUCTVY    PH       T ALK     NH3-N    TOT KJEL  NO2&NO3   PHOS-DIS
 FROM     OF        TEMP               SECCHI    FIELD                CACO3     TOTAL       N      N-TOTAL   ORTHO
  TO     DAY  FEET  CENT      MG/L     INCHES    MICROMHO    SU       MG/L      MG/L      MG/L      MG/L     MG/L P

75/05/06 11 55 0000    11.1      7.2        11      3811     8.70       107     0.320     3.200     0.050     0.115
75/08/22 11 00 0000    22.0      5.3        11      7095     8.90
75/10/07 15 20 0000    19.0      8.8         8      7083     9.40


STORET RETRIEVAL DATE 76/01/09
                                                                    081003
                                                                    38 10 42.0 103 43 31.0
                                                                    LAKE MEREDITH
                                                                    35061   COLORADO

                                                                    11EPALES            2111202
                                                                    3                   0004 FEET  DEPTH

                            00665     32217     00031
 DATE    TIME DEPTH PHOS-TOT  CHLRPHYL  INCDT LT
 FROM     OF                    A       REMNING
  TO     DAY  FEET  MG/L P     UG/L     PERCENT

75/05/06 11 55 0000   0.333      63.6
75/08/22 11 00 0000             138.0
75/10/07 15 20 0000             349.4
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STORET RETRIEVAL DATE 76/01/09
                                                                081001
                                                               38 13 12.0 103 40 13.0
                                                               LAKE MEREDITH
                                                               08025   COLORADO

                                                               11EPALES              2111202
                                                               3                    0005 FEET  DEPTH

                           00010      00300      00077      00094      00400      00410      00610      00625      00630      00671
 DATE    TIME DEPTH WATER        DO       TRANSP    CNDUCTVY      PH       T ALK      NH3-N     TOT KJEL   NO2&NO3   PHOS-DIS
 FROM     OF                TEMP                  SECCHI    FIELD                 CACO3      TOTAL        N       N-TOTAL    ORTHO
  TO      DAY  FEET    CENT        MG/L       INCHES   MICROMHO      SU        MG/L       MG/L       MG/L       MG/L      MG/L P

75/05/06 11 00 0000      12.8        7.6           11       3949       8.50        108      0.320      3.100      0.060      0.099
75/08/22 11 30 0000      23.8        5.4           10       7096       9.00
75/10/07 14 50 0000      17.7        8.0           10       7000       9.10


STORET RETRIEVAL DATE 76/01/09
                                                                081001
                                                               38 13 12.0 103 40 13.0
                                                               LAKE MEREDITH
                                                               08025   COLORADO

                                                               11EPALES              2111202
                                                               3                    0005 FEET  DEPTH

                           00665      32217      00031
 DATE    TIME DEPTH PHOS-TOT  CHLRPHYL   INCDT LT
 FROM     OF                            A        REMNING
  TO      DAY  FEET    MG/L P      UG/L      PERCENT

75/05/06 11 00 0000     0.326       46.2
75/08/22 11 30 0000                151.3
75/10/07 14 50 0000                278.2
```

```
STORET RETRIEVAL DATE 76/01/09
                                                                    081102
                                                                   40 13 39.0 104 38 25.0
                                                                   MILTON RESERVOIR
                                                                   30007    COLORADO

                                                                   11EPALES             2111202
                                                                   3                   0015 FEET  DEPTH

                          00010      00300      00077      00094       00400      00410      00610      00625      00630      00671
 DATE    TIME DEPTH      WATER        DO       TRANSP     CNDUCTVY      PH        T ALK      NH3-N    TOT KJEL   NO2&NO3   PHOS-DIS
 FROM     OF              TEMP                 SECCHI     FIELD                   CACO3      TOTAL        N      N-TOTAL     ORTHO
  TO     DAY  FEET        CENT       MG/L      INCHES     MICROMHO     SU         MG/L       MG/L       MG/L       MG/L      MG/L P

75/05/06 15 30 0000        13.2        6.2        120        1042       8.35        276      1.450      2.700      0.630      1.090
         15 30 0005        13.1        6.0                   1032                   288      1.460      2.800      0.820      1.000
         15 30 0011        12.6        5.8                   1025       8.40        276      1.770      2.700      0.820      1.090
75/08/26 10 20 0000        22.5        7.2         40        1306       9.00
         10 20 0004        21.0        7.2                   1258       9.05
75/10/10 09 30 0000        13.0        6.0         36        1087       8.20
```

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STORET RETRIEVAL DATE 76/01/09
                                                                    081102
                                                                   40 13 39.0 104 38 25.0
                                                                   MILTON RESERVOIR
                                                                   30007    COLORADO

                                                                   11EPALES             2111202
                                                                   3                   0015 FEET  DEPTH

                          00665      32217      00031
 DATE    TIME DEPTH     PHOS-TOT   CHLRPHYL   INCDT LT
 FROM     OF                           A      REMNING
  TO     DAY  FEET       MG/L P      UG/L     PERCENT

75/05/06 15 30 0000       1.160        1.4
         15 30 0005       1.170
         15 30 0011       1.160
75/08/26 10 20 0000                   16.0
75/10/10 09 30 0000                    4.3
```

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STORET RETRIEVAL DATE 76/01/09
                                                                      080901
                                                                     38 03 45.0 103 36 38.0
                                                                     HOLBROOK LAKE
                                                                     08025    COLORADO

                                                                     11EPALES              2111202
                                                                     3                    0005 FEET  DEPTH

                          00010      00300      00077      00094      00400     00410     00610     00625     00630     00671
 DATE     TIME DEPTH    WATER        DO       TRANSP    CNDUCTVY      PH      T ALK     NH3-N    TOT KJEL  NO2&NO3  PHOS-DIS
 FROM      OF            TEMP                 SECCHI    FIELD                  CACO3     TOTAL        N     N-TOTAL    ORTHO
  TO      DAY  FEET      CENT       MG/L      INCHES    MICROMHO      SU        MG/L      MG/L      MG/L      MG/L     MG/L P

75/05/06 12 30 0000       13.6                     11       1650      8.10       147     0.050     1.700    0.020K     0.028
75/08/22 10 35 0000       21.6        6.0           7       2368      8.60
75/10/07 14 30 0000       18.3                     11       1812      8.90


STORET RETRIEVAL DATE 76/01/09
                                                                      080901
                                                                     38 03 45.0 103 36 38.0
                                                                     HOLBROOK LAKE
                                                                     08025    COLORADO

                                                                     11EPALES              2111202
                                                                     3                    0005 FEET  DEPTH

                          00665      32217      00031
 DATE     TIME DEPTH  PHOS-TOT    CHLRPHYL    INCDT LT
 FROM      OF                         A       REMNING
  TO      DAY  FEET     MG/L P       UG/L     PERCENT

75/05/06 12 30 0000      0.127        28.7
75/08/22 10 35 0000                  146.9
75/10/07 14 30 0000                  160.2
```

APPENDIX B

PHOTOGRAPHIC FLIGHT LOG OF NASA AIRCRAFT COVERAGE OF COLORADO LAKES, AUGUST 25, 1975

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PHOTOGRAPHIC FLIGHT LOG

MISSION 317 SITES 185/X353 DATE 8/25/75 PHOTOGRAPHER BLUNCK PAGE 1 OF 2

CAMERA / POSITION	Zeiss 1
LENS / SERIAL NO.	6" 036
FILM / EMULSION NO	50397 52-1
FILTER / SERIAL NO	KL-36 952
SHUTTER SPEED	1/400
f/STOP	AEC
OVERLAP %	60
ROLL NUMBER	6

NOTES

DATA FLIGHT 1

WX: Clear, NO HAZE

ROLL 6, MAGAZINE 809

SITE / FLIGHT NO.	LINE	RUN	START / STOP	START / STOP	START / STOP	START / STOP	START / STOP	START / STOP	START / STOP	START / STOP	START / STOP	START / STOP	METER TIME	IVLR SEC	ABS ALT	DRIFT	TRUE HEAD	GROUND SPEED
185 8	12	1	01 05										175550 175750	27	20.9	6.4 L	222.5	264
	11	1	06 08										180040 180115	22	21.0	4.7 R	054.1	306
	7	1	09 12										181515 181630	25	19.3	5.6 L	219.3	268
	5	1	13 19										184600 184810	22	19.1	2.6 L	256.6	290
	4	1	20 25										185730 185920	22	18.6	5.8 L	170.4	294
	3	1	26 32										190330 190610	25	18.9	6.2 R	335.5	250
	5	2	33 39										191110 191320	20	19.0	4.2 R	070.8	297
	8	1	40 46										192835 193015	18	15.1	9.7 R	032.5	318
	10	1	47 51										193455 193640	25	19.1	0.9 R	292.1	245

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PHOTOGRAPHIC FLIGHT LOG (CONTINUATION SHEET)

MISSION 317/X353

DATE 8/25/75

PAGE 2 OF 2

CAMERA/POSITION			Zeiss 1															
SITE / FLIGHT NO.	LINE	RUN	START / STOP	START / STOP	START / STOP	START / STOP	START / STOP	START / STOP	START / STOP	START / STOP	START / STOP	START / STOP	TIME	IVLR. SEC	ABS KALT	DRIFT	TRUE HEAD.	GROUND SPEED
185 8	14	1	52 55										194915 195020	25	18.6	12.3 L	215.0	264
	9	1	56 59										195245 195345	17	18.7	2.0 R	096.6	336
	1	1	60 64										195900 200010	18	18.6	7.3 R	061.1	314
	13	1	66 68										200850 200945	25	19.2	8.5 L	178.6	306
	2	1	69 74										201220 201400	20	18.9	7.0 L	230.5	276
	6	1	75 78										201710 201815	20	185	6.0 L	149.3	336

COMMENTS:

m 880A (Rev Dec 71) PREVIOUS EDITION MAY BE USED. NASA — MSC

APPENDIX C

REGRESSION MODEL PREDICTED, RESIDUAL AND ASSOCIATED OBSERVED VALUES

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Table C-1. Regression Model Predicted, Residual and Associated Observed Values

Lake or Site STORET Number	Model 1 CHLA	Model 1 $\widehat{\text{CHLA}}$	Model 1 Residuals	Model 2 CHLA	Model 2 $\widehat{\text{CHLA}}$	Model 2 Residuals	Model 3 CHLA	Model 3 $\widehat{\text{CHLA}}$	Model 3 Residuals	Model 4 CHLA	Model 4 $\widehat{\text{CHLA}}$	Model 4 Residuals
0801	3.7	4.4	-0.7									
080101				3.7	3.9	-0.2						
080102				3.7	4.8	-1.1						
0802	51.7	44.2	7.5									
080201				74.4	18.5	55.9	74.4	49.5	24.9	74.4	32.6	41.8
080202				29.0	32.5	-3.5	29.0	72.5	-43.5	29.0	49.6	-20.6
0803	4.9	4.8	0.1									
080301				6.0	6.7	-0.7						
080302				4.1	7.6	-3.5						
080303				4.6	4.8	-0.2						
080304				4.2	5.3	-1.1						
080305				5.2	4.5	0.7						
080306				5.4	4.4	1.0						
0804	48.7	47.0	1.7									
080401				9.8	20.4	-10.6	9.8	5.1	4.7	9.8	11.2	-1.4
080402				124.6	29.8	94.8	124.6	37.7	86.9	124.6	57.5	67.1
080403				11.6	28.3	-16.7	11.6	20.8	-9.2	11.6	15.6	-4.0
0806	2.3	4.0	-1.7									
080601				2.2	4.5	-2.3	2.2	4.0	-1.8	2.2	1.9	0.3
080602				2.5	3.0	-0.5	2.5	4.2	-1.7	2.5	2.3	0.2
080603				2.1	4.0	-1.9	2.1	3.0	-0.9	2.1	3.0	-0.9
080604				2.4	2.6	-0.2	2.4	4.0	-1.6	2.4	1.3	1.0
0807	5.5	3.2	2.3									
080701				5.5	2.6	2.9	5.5	6.3	-0.8	5.5	6.3	-0.8
080702				5.4	2.9	2.5	5.4	2.1	3.3	5.4	10.1	-4.7
0808	8.3	12.4	-4.1									
080801				7.9	13.6	-5.7						
080802				7.1	10.1	-3.0						
080803				9.8	9.1	0.7						
0811	12.2	11.3	0.9									
081101				8.3	9.7	-1.4	8.3	6.8	1.5	8.3	8.1	0.2
081102				16.0	13.5	2.5	16.0	13.1	2.9	16.0	22.4	-6.4
0813	6.2	4.5	1.7									
081301				8.1	5.1	3.0						
081302				6.5	3.8	2.7						
081303				3.9	4.2	-0.3						
Mean	15.9	15.1	0.9	13.9	9.6	4.2	22.6	17.6	5.0	22.6	17.1	5.5
Maximum	51.7	47.0	7.5	124.6	32.5	94.8	124.6	72.5	86.9	124.6	57.5	67.1
Minimum	2.3	3.2	-4.1	2.1	2.6	-16.7	2.1	2.1	-43.5	2.1	1.4	-20.6
Range	49.4	43.7	11.6	122.5	29.9	111.5	122.5	70.4	130.4	122.5	56.1	87.7
S.D.	19.6	17.6	3.2	26.2	8.7	21.6	36.4	22.1	28.7	36.4	18.6	23.0
N	9	9	9	27	27	27	13	13	13	13	13	13

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Table C-1. Regression Model Predicted, Residual and Associated Observed Values (Continuation 1)

Lake or Site STORET Number	Model 5			Model 6			Model 7			Model 8		
	CHLA	$\widehat{CHLA}$	Residuals	CHLA	$\widehat{CHLA}$	Residuals	ISEC	$\widehat{ISEC}$	Residuals	ISEC	$\widehat{ISEC}$	Residuals
0801							0.461	0.363	0.098			
080101										0.410	0.338	0.072
080102										0.525	0.394	0.131
0802							2.187	1.612	0.575			
080201	74.4	33.1	41.3	74.4	25.9	48.5				3.281	1.147	2.134
080202	29.0	29.2	-0.2	29.0	28.2	0.8				1.640	1.785	-0.145
0803							0.490	0.386	0.104			
080301										0.547	0.515	0.032
080302										0.787	0.569	0.218
080303										0.437	0.393	0.044
080304										0.410	0.428	-0.018
080305										0.394	0.376	0.018
080306										0.525	0.368	0.157
0804							1.373	1.676	-0.303			
080401	9.8	16.4	-6.7	9.8	15.4	-5.6				1.094	1.238	-0.144
080402	124.6	75.0	49.6	124.6	84.7	39.9				1.514	1.669	-0.155
080403	11.6	17.1	-5.5	11.6	16.6	-5.0				1.640	1.603	0.037
0806							0.120	0.343	-0.223			
080601	2.2	2.4	-0.2	2.2	2.1	0.1				0.219	0.378	-0.159
080602	2.5	4.6	-2.1	2.5	5.0	-2.5				0.193	0.271	-0.078
080603	2.1	2.0	0.1	2.1	2.3	-0.2				0.066	0.342	-0.276
080604	2.4	1.0	1.4	2.4	1.0	1.4				0.156	0.245	-0.089
0807							0.398	0.298	0.100			
080701	5.5	7.2	-1.7	5.5	8.6	-3.1				0.410	0.243	0.167
080702	5.4	6.9	-1.5	5.4	8.8	-3.4				0.386	0.268	0.118
0808							0.471	0.708	-0.237			
080801										0.410	0.897	-0.487
080802										0.492	0.712	-0.220
080803										0.525	0.654	-0.129
0811							0.787	0.669	0.118			
081101	8.3	13.1	-4.8	8.3	11.0	-2.7				0.656	0.690	-0.034
081102	16.0	12.1	3.9	16.0	11.2	4.8				0.984	0.894	0.090
0813							0.562	0.368	0.194			
081301										0.656	0.415	0.241
081302										0.525	0.332	0.193
081303										0.525	0.353	0.172
Mean	22.6	16.9	5.7	26.6	17.0	5.6	0.761	0.714	0.047	0.719	0.649	0.719
Maximum	124.6	75.0	49.6	124.6	84.7	48.5	2.187	1.676	0.575	3.281	1.785	3.281
Minimum	2.1	1.0	-6.6	2.1	1.0	-5.6	0.120	0.298	-0.303	0.066	0.243	0.066
Range	122.5	74.0	56.3	122.5	83.7	54.1	1.410	1.378	0.878	3.215	1.542	3.215
S.D.	36.4	20.1	18.0	36.4	22.1	17.4	0.636	0.547	0.272	0.660	0.458	0.660
N	13	13	13	13	13	13	9	9	9	27	27	27

Table C-1. Regression Model Predicted, Residual and Associated Observed Values (Continuation 2)

Lake or Site		Model 9			Model 10			Model 11			Model 12	
STORET Number	ISEC	$\widehat{\text{ISEC}}$	Residuals	ISEC	$\widehat{\text{ISEC}}$	Residuals	ISEC	$\widehat{\text{ISEC}}$	Residuals	ISEC	$\widehat{\text{ISEC}}$	Residuals
0801												
080101												
080102												
0802												
080201	3.281	1.177	2.104	3.281	1.177	2.104	3.281	1.177	2.104	3.281	1.428	1.853
080202	1.640	2.006	-0.366	1.640	1.472	0.168	1.640	1.472	0.168	1.640	2.171	-0.531
0803												
080301												
080302												
080303												
080304												
080305												
080306												
0804												
080401	1.094	1.290	-0.196	1.094	1.004	0.090	1.094	1.004	0.090	1.094	1.042	0.052
080402	1.514	1.850	-0.336	1.514	2.783	-1.269	1.514	2.783	-1.269	1.514	1.460	0.054
080403	1.640	1.763	-0.123	1.640	1.552	0.088	1.640	1.552	0.088	1.640	2.496	-0.856
0806												
080601	0.219	0.308	-0.089	0.219	0.279	-0.060	0.219	0.279	-0.060	0.219	0.224	-0.005
080602	0.193	0.207	-0.014	0.193	0.245	-0.052	0.193	0.245	-0.052	0.193	0.168	0.025
080603	0.066	0.274	-0.208	0.066	0.143	-0.077	0.066	0.143	-0.077	0.066	0.099	-0.033
080604	0.156	0.183	-0.027	0.156	0.106	0.050	0.156	0.106	0.050	0.156	0.150	0.006
0807												
080701	0.410	0.181	0.229	0.410	0.280	0.130	0.410	0.280	0.130	0.410	0.358	0.052
080702	0.386	0.204	0.182	0.386	0.279	0.107	0.386	0.279	0.107	0.386	0.331	0.055
0808												
080801												
080802												
080803												
0811												
081101	0.656	0.637	0.019	0.656	0.924	-0.268	0.656	0.924	-0.268	0.656	1.024	-0.368
081102	0.984	0.871	0.113	0.984	1.153	-0.169	0.984	1.153	-0.169	0.984	0.817	0.167
0813												
081301												
081302												
081303												
Mean	0.942	0.843	0.099	0.942	0.877	0.065	0.942	0.877	0.065	0.942	0.905	0.036
Maximum	3.281	2.006	2.104	3.281	2.783	2.104	3.281	2.783	2.104	3.281	2.496	1.853
Minimum	0.066	0.181	-0.366	0.066	0.106	-1.269	0.066	0.106	-1.269	0.066	0.099	-0.856
Range	3.215	1.825	2.470	3.215	2.676	3.372	3.215	2.676	3.372	3.215	2.396	2.709
S.D.	0.910	0.699	0.629	0.910	0.776	0.717	0.910	0.776	0.717	0.910	0.796	0.620
N	13	13	13	13	13	13	13	13	13	13	13	13

Table C-1. Regression Model Predicted, Residual and Associated Observed Values (Continuation 3)

Lake or Site STORET Number	Model 13			Model 14			Model 15			Model 16		
	ISEC	$\widehat{ISEC}$	Residuals	SEC	$\widehat{SEC}$	Residuals	SEC	$\widehat{SEC}$	Residuals	SEC	$\widehat{SEC}$	Residuals
0801												
080101												
080102												
0802												
080201	3.281	1.398	1.883	0.31	0.85	-0.54	0.31	0.70	-0.39	0.31	0.72	-0.41
080202	1.640	2.499	-0.859	0.61	0.68	-0.07	0.61	0.46	0.15	0.61	0.40	0.21
0803												
080301												
080302												
080303												
080304												
080305												
080306												
0804												
080401	1.094	0.858	0.236	0.91	1.00	-0.09	0.91	0.96	-0.05	0.91	1.17	-0.26
080402	1.514	2.086	-0.572	0.66	0.36	0.30	0.66	0.69	-0.03	0.66	0.48	0.18
080403	1.640	2.013	-0.373	0.61	0.65	-0.04	0.61	0.40	0.21	0.61	0.50	0.11
0806												
080601	0.219	0.281	-0.062	4.57	3.59	0.98	4.57	4.49	0.08	4.57	3.58	0.99
080602	0.193	0.230	-0.037	5.18	4.08	1.10	5.18	5.96	-0.78	5.18	4.35	0.83
080603	0.066	0.149	-0.083	15.24	6.99	8.25	15.24	10.10	5.14	15.24	6.72	8.52
080604	0.156	0.125	0.031	6.40	9.43	-3.03	6.40	6.69	-0.29	6.40	8.03	-1.63
0807												
080701	0.410	0.260	0.150	2.44	3.58	-1.14	2.44	2.79	-0.35	2.44	3.85	-1.41
080702	0.386	0.258	0.128	2.59	3.59	-1.00	2.59	3.02	-0.43	2.59	3.87	-1.28
0808												
080801												
080802												
080803												
0811												
081101	0.656	0.712	-0.056	1.52	1.08	0.44	1.52	0.98	0.54	1.52	1.40	0.12
081102	0.984	0.902	0.082	1.02	0.87	0.15	1.02	1.23	-0.21	1.02	1.11	-0.09
0813												
081301												
081302												
081303												
Mean	0.942	0.905	0.036	3.24	2.83	0.41	3.24	2.96	0.28	3.24	2.78	0.45
Maximum	3.281	2.499	1.883	15.24	9.43	8.25	15.24	10.10	5.14	15.24	8.03	8.52
Minimum	0.066	0.125	-0.859	0.31	0.36	-3.03	0.31	0.40	-0.78	0.31	0.40	-1.63
Range	3.215	2.374	1.787	14.93	9.07	11.28	14.93	9.70	5.92	14.93	7.62	10.15
S.D.	0.910	0.832	0.636	4.11	2.80	2.59	4.11	3.03	1.50	4.11	2.52	2.55
N	13	13	13	13	13	13	13	13	13	13	13	13

Table C-1. Regression Model Predicted, Residual and Associated Observed Values (Continuation 4)

Lake or Site STORET Number		Model 17			Model 18			Model 19			Model 20	
	TPHOS	$\widehat{\text{TPHOS}}$	Residuals	TPHOS	$\widehat{\text{TPHOS}}$	Residuals	TPHOS	$\widehat{\text{TPHOS}}$	Residuals	TPHOS	$\widehat{\text{TPHOS}}$	Residuals
0801	0.015	0.012	0.003									
080101				0.016	0.015	0.001						
080102				0.014	0.020	-0.006						
0802	0.747	0.490	0.257									
080201				0.761	0.106	0.655	0.761	0.157	0.604	0.761	1.491	-0.730
080202				0.733	0.212	0.521	0.733	0.349	0.384	0.733	0.244	0.489
0803	0.022	0.139	-0.117									
080301				0.059	0.030	0.029						
080302				0.020	0.035	-0.015						
080303				0.019	0.020	-0.001						
080304				0.022	0.022	-0.000						
080305				0.025	0.018	0.007						
080306				0.020	0.018	0.002						
0804	0.054	0.086	-0.032									
080401				0.041	0.119	-0.078	0.041	0.181	-0.140	0.041	0.066	-0.025
080402				0.089	0.191	-0.102	0.089	0.309	-0.220	0.089	0.163	-0.074
080403				0.043	0.179	-0.136	0.043	0.288	-0.245	0.043	0.033	0.010
0806	0.009	0.007	0.002									
080601				0.008	0.018	-0.010	0.008	0.021	-0.013	0.008	0.023	-0.015
080602				0.009	0.011	-0.002	0.009	0.012	-0.003	0.009	0.007	0.002
080603				0.011	0.016	-0.005	0.011	0.018	-0.007	0.011	0.006	0.005
080604				0.006	0.009	-0.003	0.006	0.010	-0.004	0.006	0.004	0.002
0807	0.011	0.010	0.001									
080701				0.012	0.009	0.003	0.012	0.010	0.002	0.012	0.015	-0.003
080702				0.010	0.011	-0.001	0.010	0.011	-0.001	0.010	0.019	-0.009
0808	0.010	0.015	-0.005									
080801				0.009	0.072	-0.063						
080802				0.010	0.050	-0.040						
080803				0.013	0.044	-0.031						
0811	0.720	0.134	0.586									
081101				0.714	0.047	0.667	0.714	0.063	0.651	0.714	0.350	0.364
081102				0.728	0.071	0.657	0.728	0.100	0.628	0.728	0.487	0.241
0813	0.025	0.024	0.001									
081301				0.049	0.021	0.028						
081302				0.021	0.015	0.006						
081303				0.018	0.017	0.001						
Mean	0.179	0.102	0.077	0.129	0.052	0.077	0.245	0.118	0.126	0.245	0.224	0.120
Maximum	0.747	0.490	0.586	0.761	0.212	0.667	0.761	0.349	0.651	0.761	1.491	0.489
Minimum	0.009	0.007	-0.117	0.006	0.009	-0.136	0.006	0.009	-0.245	0.006	0.004	-0.730
Range	0.738	0.483	0.703	0.755	0.203	0.803	0.755	0.340	0.896	0.755	1.487	1.220
S.D.	0.314	0.155	0.215	0.258	0.059	0.237	0.341	0.127	0.323	0.341	0.411	0.284
N	9	9		27	27	27	13	13	13	13	13	13

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Table C-1. Regression Model Predicted, Residual and Associated Observed Values (Continuation 5)

Lake or Site STORET Number		Model 21			Model 22			Model 23			Model 24	
	TPHOS	$\widehat{\text{TPHOS}}$	Residuals	TPHOS	$\widehat{\text{TPHOS}}$	Residuals	TON	$\widehat{\text{TON}}$	Residuals	TON	$\widehat{\text{TON}}$	Residuals
0801							0.180	0.220	-0.040			
080101										0.180	0.201	-0.021
080102										0.180	0.234	-0.054
0802							1.623	1.219	0.404			
080201	0.761	0.561	0.200	0.761	0.979	-0.218				1.890	0.689	1.201
080202	0.733	0.153	0.580	0.733	0.629	0.104				1.357	1.076	0.281
0803							0.277	0.273	0.004			
080301										0.380	0.307	0.073
080302										0.180	0.340	-0.160
080303										0.180	0.234	-0.054
080304										0.197	0.255	-0.058
080305										0.143	0.224	-0.081
080306										0.150	0.219	-0.069
0804							0.816	1.151	-0.335			
080401	0.041	0.103	-0.062	0.041	0.045	-0.004				0.533	0.744	-0.211
080402	0.089	0.192	-0.103	0.089	0.146	-0.057				1.130	1.005	0.125
080403	0.043	0.074	-0.031	0.043	0.038	0.005				0.710	0.966	-0.256
0806							0.190	0.191	-0.001			
080601	0.008	0.054	-0.046	0.008	0.023	-0.015				0.200	0.225	-0.025
080602	0.009	0.010	-0.001	0.009	0.005	0.004				0.180	0.161	0.019
080603	0.011	0.006	0.005	0.011	0.008	0.003				0.180	0.204	-0.024
080604	0.006	0.006	0.000	0.006	0.006	0.000				0.158	0.145	0.013
0807							0.116	0.141	-0.025			
080701	0.012	0.008	0.004	0.012	0.012	0.000				0.180	0.144	0.036
080702	0.010	0.008	0.002	0.010	0.021	-0.011				0.197	0.159	0.038
0808							0.237	0.472	-0.235			
080801										0.180	0.537	-0.357
080802										0.180	0.426	-0.246
080803										0.380	0.391	-0.011
0811							1.092	0.600	0.492			
081101	0.714	0.354	0.360	0.714	0.171	0.543				1.050	0.412	0.638
081102	0.728	0.529	0.199	0.728	0.782	-0.054				1.155	0.535	0.620
0813							0.320	0.187	0.133			
081301										0.330	0.247	0.083
081302										0.347	0.197	0.150
081303										0.330	0.210	0.120
Mean	0.245	0.158	0.085	0.245	0.220	0.232	0.539	0.495	0.044	0.454	0.388	0.066
Maximum	0.761	0.561	0.580	0.761	0.979	0.543	1.623	1.219	0.492	1.890	1.076	1.206
Minimum	0.006	0.006	-0.103	0.006	0.005	-0.218	0.116	0.141	-0.335	0.143	0.144	-0.357
Range	0.755	0.556	0.684	0.755	0.974	0.761	1.507	1.077	0.827	1.740	0.932	1.558
S.D.	0.341	0.199	0.198	0.341	0.340	0.171	0.524	0.419	0.268	0.458	0.276	0.317
N	13	13	13	13	13	13	9	9	9	27	27	27

Table C-1. Regression Model Predicted, Residual and Associated Observed Values (Continuation 6)

Lake or Site STORET Number	Model 25			Model 26			Model 27			Model 28		
	TON	$\widehat{TON}$	Residuals	TON	$\widehat{TON}$	Residuals	TON	$\widehat{TON}$	Residuals	TON	$\widehat{TON}$	Residuals
0801												
080101												
080102												
0802												
080201	1.890	0.881	1.009	1.890	1.923	-0.044	1.890	1.927	-0.037	1.890	1.591	0.299
080202	1.357	1.406	-0.049	1.357	1.149	0.208	1.357	1.184	0.173	1.357	1.738	-0.381
0803												
080301												
080302												
080303												
080304												
080305												
080306												
0804												
080401	0.533	0.955	-0.422	0.533	0.680	-0.147	0.533	0.629	-0.096	0.533	0.521	0.012
080402	1.130	1.310	-0.180	1.130	1.072	0.058	1.130	1.173	-0.043	1.130	1.048	0.082
080403	0.710	1.255	-0.545	0.710	0.798	-0.088	0.710	0.628	0.082	0.710	0.685	0.025
0806												
080601	0.200	0.272	-0.072	0.200	0.337	-0.137	0.200	0.317	-0.117	0.200	0.273	-0.073
080602	0.180	0.192	-0.012	0.180	0.183	-0.003	0.180	0.204	-0.024	0.180	0.160	0.020
080603	0.180	0.245	-0.065	0.180	0.147	0.033	0.180	0.143	0.037	0.180	0.156	0.024
080604	0.158	0.172	-0.014	0.158	0.129	0.029	0.158	0.114	0.044	0.158	0.131	0.027
0807												
080701	0.180	0.171	0.009	0.180	0.199	-0.019	0.180	0.217	-0.037	0.180	0.218	-0.038
080702	0.197	0.189	0.008	0.197	0.192	0.005	0.197	0.213	-0.016	0.197	0.261	-0.064
0808												
080801												
080802												
080803												
0811												
081101	1.050	0.515	0.535	1.050	0.891	0.159	1.050	0.921	0.129	1.050	0.726	0.324
081102	1.155	0.677	0.478	1.155	0.947	0.208	1.155	1.016	0.139	1.155	1.263	-0.108
0813												
081301												
081302												
081303												
Mean	0.686	0.634	0.052	0.686	0.666	0.020	0.686	0.668	0.018	0.686	0.675	0.012
Maximum	1.890	1.406	1.009	1.890	1.934	0.208	1.890	1.927	0.173	1.890	1.738	0.324
Minimum	0.158	0.171	-0.545	0.158	0.129	-0.147	0.158	0.114	-0.117	0.158	0.131	-0.381
Range	1.732	1.235	1.554	1.732	1.805	0.355	1.732	1.813	0.290	1.732	1.606	0.705
S.D.	0.577	0.476	0.410	0.577	0.540	0.116	0.577	0.550	0.091	0.577	0.567	0.176
N	13	13	13	13	13	13	13	13	13	13	13	13

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Table C-1. Regression Model Predicted, Residual and Associated Observed Values (Continuation 7)

Lake or Site STORET Number	Model 29			Model 30			Model 31			Model 32		
	COND	$\widehat{\text{COND}}$	Residuals	COND	$\widehat{\text{COND}}$	Residuals	COND	$\widehat{\text{COND}}$	Residuals	COND	$\widehat{\text{COND}}$	Residuals
0801	30	57	-27									
080101				29	44	-15						
080102				32	53	-21						
0802	595	747	-152									
080201				597	896	-299	597	555	42	597	173	424
080202				593	589	4	593	1231	-638	593	502	91
0803	152	156	-4									
080301				123	156	-34						
080302				132	178	-46						
080303				160	109	51						
080304				167	86	81						
080305				180	116	64						
080306				180	89	91						
0804	600	426	174									
080401				637	1149	-512	637	637	0	637	424	213
080402				586	849	-263	586	1091	-506	586	680	-94
080403				571	187	384	571	1015	-444	571	1860	-1289
0806	92	32	60									
080601				89	96	-7	89	75	14	89	236	-147
080602				93	34	59	93	41	52	93	40	53
080603				91	28	63	91	63	28	91	34	57
080604				89	35	54	89	34	55	89	52	37
0807	7	11	4									
080701				8	17	-9	8	34	-26	8	25	-17
080702				5	27	-22	5	40	-35	5	27	-22
0808	107	177	-70									
080801				109	394	-285						
080802				105	127	-22						
080803				109	142	-33						
0811	1295	1055	240									
081101				1304	668	636	1304	222	1082	1304	511	793
081102				1282	368	914	1282	354	928	1282	1319	-38
0813	24	19	5									
081301				24	39	-15						
081302				25	35	-10						
081303				24	39	-15						
Mean	322	298	25	272	242	29	457	415	43	457	452	5
Maximum	1295	1055	240	1304	1150	914	1304	1232	1082	1304	1860	793
Minimum	7	11	-152	5	17	-512	5	34	-639	5	25	-1289
Range	1288	1045	392	1299	1133	1427	1299	1198	1721	1299	1835	2082
S.D.	433	373	120	359	312	271	451	448	490	451	562	462
N	9	9	9	27	27	27	13	13	13	13	13	13

Table C-1. Regression Model Predicted, Residual and Associated Observed Values (Continuation 8)

Lake or Site STORET Number	Model 33			Model 34			Model 35			Model 36		
	COND	$\widehat{COND}$	Residuals	COND	$\widehat{COND}$	Residuals	AAY	$\widehat{AAY}$	Residuals	AAY	$\widehat{AAY}$	Residuals
0801							0.5	0.4	0.1			
080101										0.5	0.9	-0.4
080102										0.5	0.6	-0.1
0802							186.3	139.4	46.9			
080201	597	173	424	597	267	330				186.3	9.9	176.4
080202	593	502	91	593	463	130				186.3	29.6	156.7
0803							0.7	3.6	-2.9			
080301										0.4	0.3	0.1
080302										0.4	1.7	-1.3
080303										0.4	0.4	0.0
080304										0.9	2.4	-1.5
080305										0.9	0.3	0.6
080306										0.9	0.3	0.6
0804							3.2	3.0	0.2			
080401	637	424	213	637	332	304				3.2	3.6	-0.4
080402	586	680	-94	586	1366	-780				3.2	18.7	-15.5
080403	571	1860	-1289	571	478	93				3.2	11.5	-8.3
0806							0.3	0.3	0.0			
080601	89	236	-147	89	69	20				0.3	0.4	-0.1
080602	93	40	53	93	88	5				0.3	0.2	0.1
080603	91	34	57	91	44	47				0.3	0.3	0.0
080604	89	52	37	89	28	61				0.3	0.2	0.1
0807							0.2	0.2	0.0			
080701	8	25	-17	8	114	-106				0.2	0.3	-0.1
080702	5	27	-22	5	123	-118				0.2	0.2	0.0
0808							0.3	0.5	-0.2			
080801										0.3	0.7	-0.4
080802										0.3	1.4	-1.1
080803										0.3	0.9	-0.6
0811							7.2	2.2	5.0			
081101	1304	511	793	1304	290	1040				7.2	1.6	5.6
081102	1282	1320	-38	1282	422	859				7.2	3.7	3.5
0813							0.5	0.4	0.1			
081301										0.5	0.4	0.1
081302										0.5	0.7	-0.2
081303										0.5	0.5	0.0
Mean	457	452	5	457	315	143	22.1	16.7	5.5	15.1	3.4	11.6
Maximum	1304	1860	793	1304	1366	1014	186.3	139.4	46.9	186.3	29.6	176.3
Minimum	5	25	-1288	5	28	-780	0.2	0.2	-2.9	0.2	0.2	-15.5
Range	1299	1835	2082	1299	1339	1794	186.1	139.2	49.8	186.1	29.4	191.9
S.D.	451	562	462	451	355	444	61.6	46.0	15.7	49.4	6.8	44.9
N	13	13	13	13	13	13	9	9	9	27	27	27

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Table C-1. Regression Model Predicted, Residual and Associated Observed Values (Continuation 9)

Lake or Site STORET Number	Model 37			Model 38			Model 39			Model 40		
	AAY	$\widehat{AAY}$	Residuals	AAY	$\widehat{AAY}$	Residuals	AAY	$\widehat{AAY}$	Residuals	AAY	$\widehat{AAY}$	Residuals
0801												
080101												
080102												
0802												
080201	186.3	192.0	-5.7	186.3	259.3	-73.0	186.3	192.0	-5.7	186.3	117.0	69.3
080202	186.3	19.4	166.9	186.3	112.1	74.2	186.3	19.4	166.9	186.3	125.9	60.4
0803												
080301												
080302												
080303												
080304												
080305												
080306												
0804												
080401	3.2	7.4	-4.2	3.2	1.7	1.5	3.2	7.4	-4.2	3.2	1.8	1.4
080402	3.2	14.0	-10.8	3.2	4.1	-0.9	3.2	14.0	-10.8	3.2	3.2	0.0
080403	3.2	6.3	-3.0	3.2	5.0	-1.8	3.2	6.3	-3.1	3.2	6.8	-3.6
0806												
080601	0.3	0.8	-0.5	0.3	1.1	-0.8	0.3	0.8	-0.5	0.3	1.1	-0.8
080602	0.3	0.3	0.0	0.3	0.3	0.0	0.3	0.3	0.0	0.3	0.1	0.2
080603	0.3	0.7	-0.4	0.3	0.2	0.1	0.3	0.7	-0.4	0.3	0.2	0.1
080604	0.3	0.2	0.1	0.3	0.2	0.1	0.3	0.2	0.1	0.3	0.3	0.0
0807												
080701	0.2	0.1	0.1	0.2	0.3	-0.1	0.2	0.1	0.1	0.2	0.2	0.0
080702	0.2	0.2	0.0	0.2	0.3	-0.1	0.2	0.2	0.0	0.2	0.3	-0.1
0808												
080801												
080802												
080803												
0811												
081101	7.2	4.1	3.1	7.2	4.7	2.5	7.2	4.1	3.1	7.2	4.4	2.8
081102	7.2	3.1	4.1	7.2	5.5	1.7	7.2	3.1	4.1	7.2	13.8	-6.6
0813												
081301												
081302												
081303												
Mean	30.6	19.1	11.5	30.6	30.4	0.3	30.6	19.1	0.3	30.6	21.2	9.5
Maximum	186.3	192.0	166.9	186.3	259.3	74.3	186.3	192.0	74.2	186.3	125.9	69.3
Minimum	0.2	0.1	-10.8	0.2	0.2	-73.0	0.2	0.1	-73.0	0.2	0.1	-6.6
Range	186.1	191.9	177.7	186.1	259.1	147.2	186.1	191.9	147.2	186.1	125.8	76.9
S.D.	69.1	52.3	46.9	69.1	75.2	30.1	69.1	52.3	30.1	69.1	44.7	24.8
N	13	13	13	13	13	13	13	13	13	13	13	13

Table C-1. Regression Model Predicted, Residual and Associated Observed Values (Continuation 10)

Lake or Site STORET Number		Model 41			Model 42			Model 43			Model 44	
	PC1-11	$\widehat{\text{PC1-11}}$	Residuals	PC1-27	$\widehat{\text{PC1-27}}$	Residuals	PC1-13	$\widehat{\text{PC1-13}}$	Residuals	PC1-13	$\widehat{\text{PC1-13}}$	Residuals
0801	-1.95	-2.16	0.21									
080101				-1.41	-1.34	-0.07						
080102				-1.30	-0.89	-0.41						
0802	2.90	2.62	0.28									
080201				5.43	2.29	3.14	5.43	5.18	0.25	5.43	5.41	0.02
080202				4.49	3.60	0.89	4.49	4.67	-0.18	4.49	4.20	0.29
0803	-1.17	-0.20	-0.97									
080301				0.02	-0.09	0.11						
080302				-0.66	0.21	-0.87						
080303				-0.88	-0.89	0.01						
080304				-0.65	-0.64	-0.01						
080305				-0.71	-1.02	0.31						
080306				-0.59	-1.09	0.50						
0804	1.11	1.52	-0.41									
080401				1.54	2.51	-0.97	1.54	2.04	-0.50	1.54	1.95	-0.41
080402				3.39	3.40	-0.01	3.39	4.21	-0.82	3.39	3.52	-0.13
080403				1.96	3.28	-1.32	1.96	1.72	0.24	1.96	3.14	-1.18
0806	-2.52	-2.69	0.17									
080601				-1.93	-1.01	-0.92	-1.93	-0.69	-1.24	-1.93	-0.88	-1.05
080602				-1.96	-1.99	0.03	-1.96	-1.73	-0.23	-1.96	-2.03	0.07
080603				-2.11	-1.30	-0.81	-2.51	-2.38	-0.13	-2.51	-2.56	0.05
080604				-2.28	-2.30	0.02	-2.28	-1.77	-0.51	-2.28	-3.15	0.87
0807	-2.59	-2.61	0.02									
080701				-1.85	-2.32	0.47	-1.85	-2.05	0.20	-1.85	-1.38	-0.47
080702				-2.01	-2.03	0.02	-2.01	-2.91	0.90	-2.01	-1.54	-0.47
0808	-1.49	-1.09	-0.40									
080801				-1.06	1.56	-2.62						
080802				-0.99	0.87	-1.86						
080803				-0.33	0.62	-0.95						
0811	1.50	0.60	0.90									
081101				2.78	0.78	2.00	2.78	2.03	0.75	2.78	1.92	0.86
081102				3.31	1.55	1.76	3.31	2.05	1.26	3.31	1.76	1.55
0813	-1.41	-1.59	0.18									
081301				-0.23	-0.73	0.50						
081302				-0.64	-1.40	0.76						
081303				-0.94	-1.21	0.27						
Mean	-0.62	-0.62	0.00	0.014	0.014	0.00	0.80	0.80	0.00	0.80	0.80	0.00
Maximum	2.90	2.62	0.90	5.43	3.60	3.14	5.43	5.18	1.26	5.43	5.41	1.55
Minimum	-2.59	-2.69	-0.97	-2.28	-2.32	-2.62	-2.51	-2.91	-1.24	-2.51	-3.15	-1.18
Range	5.49	5.31	1.86	7.71	5.92	5.77	7.94	8.09	2.50	7.94	8.56	2.74
S.D.	1.96	1.89	0.67	2.15	1.81	1.19	2.95	2.86	0.86	2.95	2.85	0.84
N	9	9	9	27	27	27	13	13	13	13	13	13

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Table C-1. Regression Model Predicted, Residual and Associated Observed Values (Continuation 11)

Lake or Site STORET Number	Model 45 PC1-13	 $\widehat{\text{PC1-13}}$	 Residuals	Model 46 PC1-13	 $\widehat{\text{PC1-13}}$	 Residuals
0801						
080101						
080102						
0802						
080201	5.43	5.45	-0.02	5.43	4.70	0.73
080202	4.49	3.92	0.57	4.49	5.05	-0.56
0803						
080301						
080302						
080303						
080304						
080305						
080306						
0804						
080401	1.54	1.62	-0.08	1.54	1.13	0.41
080402	3.39	3.64	-0.25	3.39	3.15	0.24
080403	1.96	1.62	0.34	1.96	2.22	-0.26
0806						
080601	-1.93	-0.58	-1.35	-1.93	-0.78	-1.15
080602	-1.96	-1.68	-0.28	-1.96	-2.51	0.55
080603	-2.51	-2.79	0.28	-2.51	-2.56	0.05
080604	-2.28	-3.61	1.33	-2.28	-3.00	0.72
0807						
080701	-1.85	-1.40	-0.45	-1.85	-1.63	-0.22
080702	-2.01	-1.48	-0.53	-2.01	-1.14	-0.87
0808						
080801						
080802						
080803						
0811						
081101	2.78	2.73	0.05	2.78	2.06	0.72
081102	3.31	2.92	0.39	3.31	3.67	-0.36
0813						
081301						
081302						
081303						
Mean	0.80	0.80	0.00	0.80	0.80	0.00
Maximum	5.43	5.45	1.33	5.43	5.05	0.74
Minimum	-2.51	-3.61	-1.35	-2.51	-3.00	-1.15
Range	7.94	9.06	2.68	7.94	8.05	1.88
S.D.	2.95	2.88	0.86	2.95	2.88	0.73
N	13	13	13	13	13	13

Table C-2. Regression Models Developed from Water Truth and MSS and MMS Data

Model Number	Dependent Variable	Intercept Value	Independent Variables and Associated Coefficients	Regression, Residual d.f.	Calculated F-value	R^2x100	Standard Error of Estimate	Comments
1	LNCHLA	-3.036	+0.233 RED	1, 7	64.87	90.26	0.36	Nine lakes. LANDSAT MSS.
2	LNCHLA	-3.367	+0.142 GRN	1, 25	44.07	63.80	0.59	Twenty-seven sites. LANDSAT MSS.
3	LNCHLA	0.728	+0.449 IR1; -1.039 IR2	2, 10	15.35	75.43	0.72	Thirteen sites. LANDSAT MSS.
4	LNCHLA	-25.628	+0.358 CH1; -0.220 CH2; +0.207 CH7	3, 9	20.49	87.23	0.55	Thirteen sites. MMS. Eight channel selection
5	LNCHLA	-9.281	+0.081 CH4; +0.156 CH9	2, 10	30.71	86.00	0.54	Thirteen sites. MMS. Channel selection limited to 4,7,8,9.
6	LNCHLA	-12.901	+0.059 MMSPC1; +0.001 MSSPC2	2, 10	24.69	83.16	0.60	Thirteen sites. MMS. Eight principal component-derived "new" channels.
7	LNISEC	-3.931	+0.150 RED	1, 7	13.76	66.28	0.51	Nine lakes. LANDSAT MSS.
8	LNISEC	-4.817	+0.112 GRN	1, 25	36.34	59.25	0.52	Twenty-seven sites. LANDSAT MSS.
9	LNISEC	-5.811	+0.135 GRN	1, 11	27.92	71.73	0.64	Thirteen sites. LANDSAT MSS.
10	LNISEC	-8.120	+0.119 CH4	1, 11	52.78	82.75	0.50	Thirteen sites. MMS. Eight channel selection.
11	LNISEC	-8.120	+0.119 CH4	1, 11	52.78	82.75	0.50	Thirteen sites. MMS. Channel selection limited to 4,7,8,9.
12	LNISEC	9.474	+0.051 MMSPC1; -0.115 MMSPC3; -1.519 MMSPC7	3, 9	30.23	90.97	0	Thirteen sites. MMS. Eight principal component-derived "new" channels.
13	LNISEC	-6.165	+0.051 MMSPC1; -0.115 MMSPC3	2, 10	29.11	85.34	0.48	Thirteen sites. MMS. Selection limited to first four components of principal component transformed eight channels.
	LNSEC		(NO MODEL DEVELOPED)					Nine lakes. LANDSAT MSS.
	LNSEC		(NO MODEL DEVELOPED)					Twenty-seven, sites. LANDSAT MSS.

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Table C-2. Regression Models Developed from Water Truth and MSS and MMS Data (Continuation 1)

Model Number	Dependent Variable	Intercept Value	Independent Variables and Associated Coefficients	Regression, Residual d.f.	Calculated F-value	R^2x100	Standard Error of Estimate	Comments
	LNSEC		(NO MODEL DEVELOPED)					Thirteen sites. LANDSAT MSS.
	LNSEC		(NO MODEL DEVELOPED)					Thirteen sites. MMS.
14	LNSEC	8.119	-0.119 CH4	1, 11	53.24	82.88	0.49	Thirteen sites. MMS. Channel selection limited to 4,7,8,9.
15	LNSEC	-9.520	-0.051 MMSPC1; +0.114 MMSPC3; +1.527 MMSPC7	3, 9	30.78	91.12	0.39	Thirteen sites. MMS. Eight principal component-derived "new" channels.
16	LNSEC	6.196	-0.051 MMSPC1; +0.114 MMSPC3	2, 10	29.29	85.42	0.48	Thirteen sites. MMS. Selection limited to first four components of principal component transformed eight channels.
17	LNTPHOS	-3.746	+0.575 IR1; -1.301 IR2	2, 6	7.63	71.75	1.07	Nine lakes. LANDSAT MSS.
18	LNTPHOS	-10.053	+0.176 GRN	1, 25	18.26	41.84	1.15	Twenty-seven sites. LANDSAT MSS.
19	LNTPHOS	-10.785	+0.201 GRN	1, 11	12.70	53.59	1.41	Thirteen sites. LANDSAT MSS.
20	LNTPHOS	-16.360	+0.442 CH2; -0.768 CH3; +0.712 CH4 -0.462 CH7	4, 8	16.64	89.27	0.79	Thirteen sites. MMS. Eight channel selection.
21	LNTPHOS	-8.947	+0.437 CH4; -0.463 CH7	2, 10	20.53	80.42	0.96	Thirteen sites. MMS channel selection limited to 4,7,8,9.
22	LNTPHOS	-28.507	+0.071 MMSPC1; -0.190 MMSPC3; -0.559 MMSPC4	3, 9	28.38	90.44	0.71	Thirteen sites. MMS. Eight principal component-derived "new" channels.
23	LNTON	-6.511	+0.143 GRN	1, 7	25.99	78.78	0.45	Nine lakes. LANDSAT MSS.
24	LNTON	-5.367	+0.113 GRN	1, 25	37.94	60.28	0.51	Twenty-seven sites. LANDSAT MSS.
25	LNTON	-5.363	+0.118 GRN	1, 11	41.83	79.18	0.45	Thirteen sites. LANDSAT MSS.
26	LNTON	-4.793	-0.091 CH3; +0.253 CH4; -0.104 CH7	3, 9	58.23	95.10	0.24	Thirteen sites. MMS. Eight channel selection.

Table C-2. Regression Models Developed from Water Truth and MSS and MMS Data (Continuation 2)

Model Number	Dependent Variable	Intercept Value	Independent Variables and Associated Coefficients	Regression, Residual d.f.	Calculated F-value	R^2x100	Standard Error of Estimate	Comments
27	LNTON	-6.449	+0.167 CH4; -0.190 CH7; +0.076 CH8	3, 9	59.69	95.21	0.24	Thirteen sites. MMS channel selection limited to 4,7,8,9.
28	LNTON	-10.732	+0.041 MMSPC1; -0.101 MMSPC3; -0.170 MMSPC4	3, 9	59.80	95.22	0.24	Thirteen sites. MMS. Eight principal component-derived "new" channels.
29	LNCOND	-11.690	+0.882 GRN; -0.807 RED	2, 6	29.53	90.78	0.60	Nine lakes. LANDSAT MSS.
30	LNCOND	-6.277	+0.493 GRN; -0.360 RED	2, 24	31.38	72.33	0.79	Twenty-seven sites. LANDSAT MSS.
31	LNCOND	-2.618	+0.201 GRN	1, 11	19.46	63.89		Thirteen sites. LANDSAT MSS.
32	LNCOND	2.251	+0.255 CH4; -0.326 CH9	2, 10	12.85	72.00	1.05	Thirteen sites. MMS. Eight channel selection.
33	LNCOND	2.251	+0.255 CH4; -0.326 CH9	2, 10	12.85	72.00	1.05	Thirteen sites. MMS channel selection limited to 4,7,8,9.
34	COND	-4616.1	+15.362 MMSPC1; -48.91 MMSPC2; -101.85 MMSPC4	3, 9	13.45	81.76	70.33	Thirteen sites. MMS. Eight principal component-derived "new" channels.
35	LNAAY	-6.285	+0.823 IR1; -0.954 IR2	2, 6	21.37	87.69	0.79	Nine lakes. LANDSAT MSS.
36	LNAAY	-7.481	+0.190 GRN; +0.246 IR1; -0.634 IR2	3, 23	13.84	64.35	1.16	Twenty-seven sites. LANDSAT MSS.
37	LNAAY	-13.288	+0.439 GRN; -0.376 RED; +0.392 IR1	3, 9	15.21	83.53	1.13	Thirteen sites. LANDSAT MSS.
38	LNAAY	-12.273	+0.289 CH4; -0.654 CH7; +0.835 CH8 -0.460 CH9	4, 8	39.22	95.15	0.65	Thirteen sites. MMS. Eight channel selection.
39	LNAAY	-12.273	+0.289 CH4; -0.654 CH7; +0.835 CH8 -0.460 CH9	4, 8	39.22	95.15	0.65	Thirteen sites. MMS channel selection limited to 4,7,8,9.
40	LNAAY	-12.841	+0.081 MMSPC1; -0.0446 MMSPC3; -0.462 MMSPC4	3, 9	41.32	93.23	0.73	Thirteen sites. MMS. Eight principal component-derived "new" channels.
41	PC1-9	-5.359	+0.218 RED; +0.421 IR1; -1.036 IR2	3, 5	21.06	92.67	0.67	Nine lakes. LANDSAT MSS.

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Table C-2. Regression Models Developed from Water Truth and MSS and MMS Data (Continuation 3)

Model Number	Dependent Variable	Intercept Value	Independent Variables and Associated Coefficients	Regression, Residual d.f.	Calculated F-value	R^2x100	Standard Error of Estimate	Comments
42	PC1-27	-12.414	+0.331 GRN	1, 25	59.59	70.45	1.19	Twenty-seven sites. LANDSAT MSS.
43	PC1-13	-13.153	+0.539 GRN; -0.442 RED; +0.632 IR1 -1.332 IR2	4, 8	33.22	94.32	0.86	Thirteen sites.. LANDSAT MSS.
44	PC1-13	-12.617	-0.476 CH3; +0.797 CH4	2, 10	68.14	93.16	0.84	Thirteen sites. MMS. Eight channel selection.
45	PC1-13	-17.912	+0.480 CH4; -0.595 CH7; +0.305 CH8	3, 9	60.89	95.30	0.86	Thirteen sites. MMS. Channel selection limited to 4,7,8,9.
46	PC1-13	-27.289	+0.126 MMSPC1; -0.348 MMSPC3; -0.497 MMSPC4	3, 9	62.93	95.45	0.73	Thirteen sites. MMS. Selection limited to first four component of principal component transformed eight channels.